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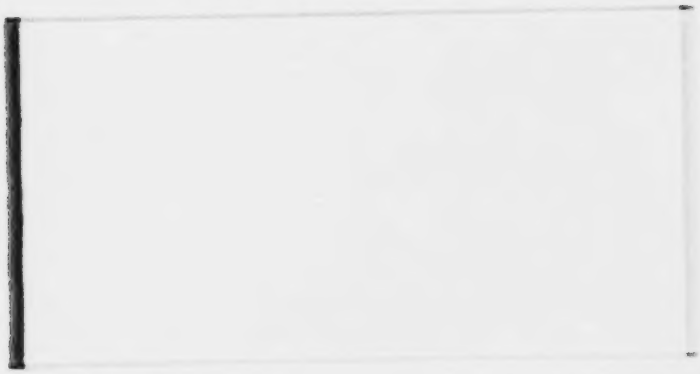

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A PRELIMINARY STUDY OF THE DISPERSION CLIMATOLOGY OF THE BRUCE AREA

Report No 86-6-K

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ABSTRACT

This report presents a preliminary study of the dispersion climatology at Bruce in 1984-1985. The frequency distributions of the occurrence of surface wind velocity, surface-based and elevated inversions and the thermal internal boundary layer were analyzed based on observational data. A generalized lake breeze index was derived to predict lake breeze days and non-lake beeze days. As well, a case was discussed to provide a real example of the dispersion climatology which occurred in the Bruce area.

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EXECUTIVE SUMMARY

A PRELIMINARY STUDY OF THE DISPERSION CLIMATOLOGY OF THE BRUCE AREA

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A year-long study was carried out in the Bruce nuclear facility to collect local meteorological information between July, 1984 and June, 1985. The instrumentation used in the study included one monostatic and one bistatic acoustic sounder, two net pyrradiometers, two anemometers and two thermographs. The collected data were analyzed to give seasonal and diurnal frequencies of occurrence of wind velocity, surface-based and elevated inversions and thermal internal boundary layers.

It was found that approximately 40% of the total observed winds during the study period were onshore with an overall average speed of 13 km/h. During the onshore flow days, the atmosphere was stable in the early morning and late evening hours but unstable in the daytime. The formation of the thermal internal boundary layer was observed on 30% of the daytime onshore flow hours.

A generalized lake breeze index was derived to predict lake breeze days and non-lake breeze days. The index makes use of the surface geostrophic wind and the difference between the lake and land surface temperatures in the Bruce area. A critical value of 10 was found to delineate the potential lake breeze and non-lake breeze days.

A detailed case study of the observed meteorology and the likely behaviour of low-level and high-level emissions at Bruce was carried out. High ground-level concentrations, produced by looping might be expected. The lake breeze circulation may enhance higher than normal concentrations in the vicinity of the generating station.

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Mr. F.J. Kee
Director of Research

A PRELIMINARY STUDY OF THE DISPERSION CLIMATOLOGY OF THE BRUCE AREA

1.0 INTRODUCTION

The Bruce Nuclear Power Development (BNPD) is the largest nuclear facility in the Ontario Hydro power system. The facility consists of three nuclear generating stations (Bruce NGS A and B and Douglas Point NGS); three heavy water plants; one steam supply plant and a bulk steam system; facilities to process and store low-level and intermediate-level radioactive waste and various administration and service buildings. A plan layout of the main building area of the facility is displayed in Figure 1.

The principal sources of emissions within BNPD are radioactive materials emitted from power generating stations and pollutants emitted from heavy water and steam supply plants. The former are likely to be emitted from the roof of the reactor buildings and/or the vacuum buildings. The reactor buildings of Bruce NGS A and B are rectangular in shape and about 49.5 m in height. The vacuum buildings are cylindrical in shape and about 46.5 m in height. Thus, emissions from these buildings may be considered as low-level emissions. On the other hand, emissions from the steam supply plant are released from a tall stack and emissions from the heavy water plant through tall flare stacks. These stacks are 100 m in height. Accordingly, these emissions may be considered as high-level emissions. It should be noted that the main pollutant emitted from the heavy water and steam supply plants is sulfur dioxide. Secondary pollutants are hydrogen sulfide that does not go to the flare stack or that escapes from the flare as a result of incomplete combustion, and oxides of nitrogen emitted by the stacks and from the flares.

The dispersion of emissions from these sources is highly dependent upon local terrain features and climatology. As shown in Figure 2, BNPD is located on the east shore of Lake Huron.

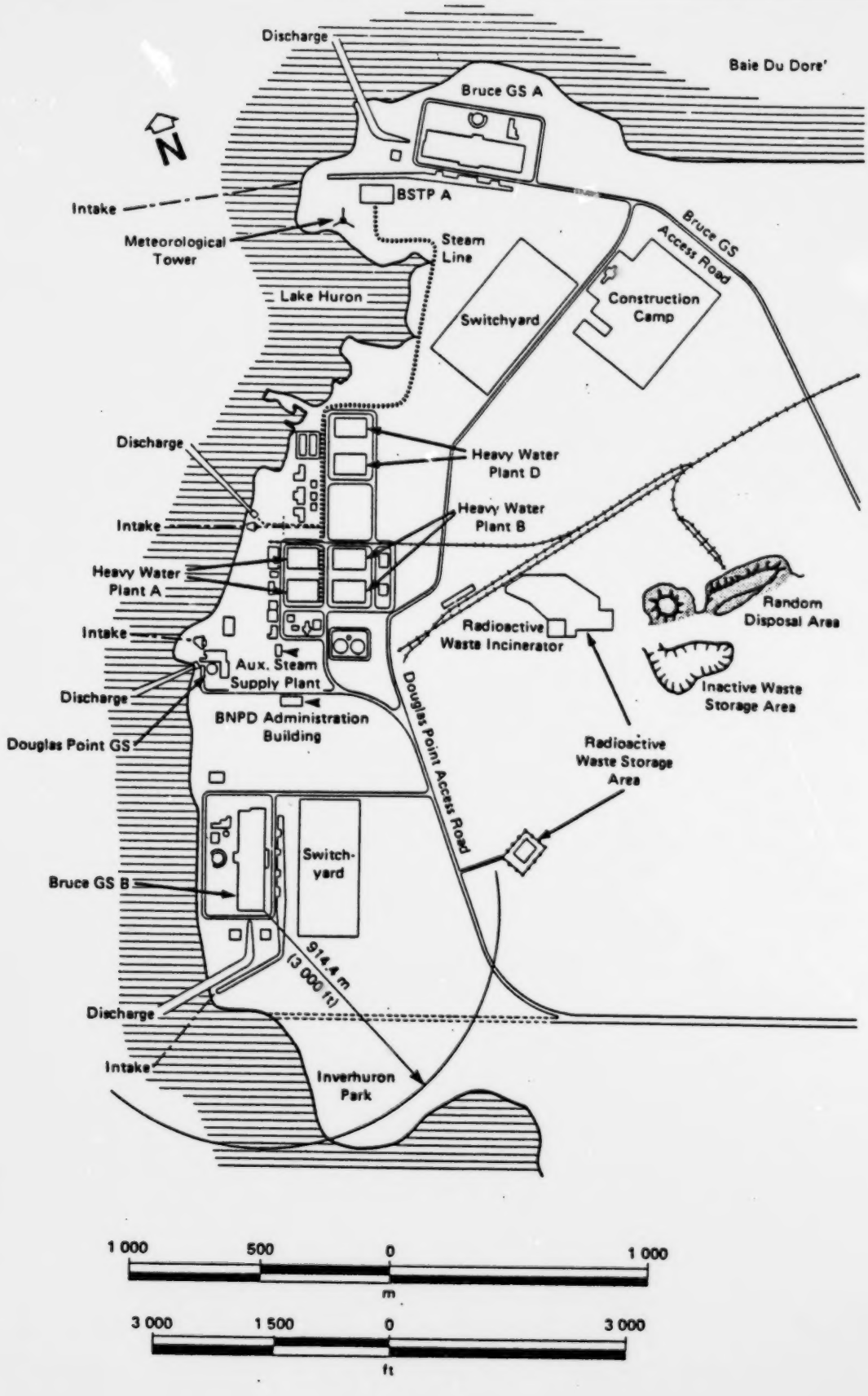

FIGURE 1

The Layout of the Main Building Area
of the Bruce Nuclear Power Development

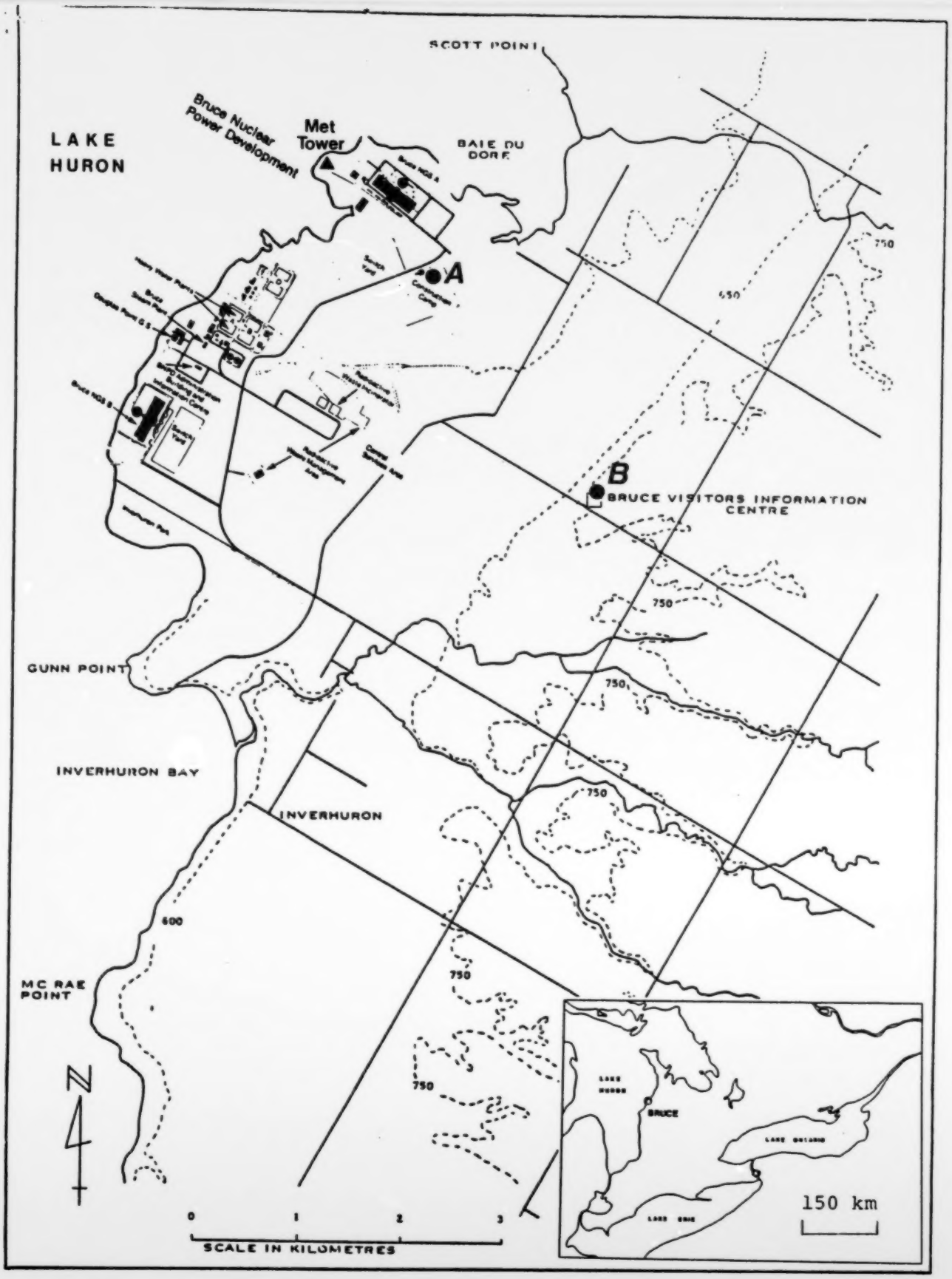

FIGURE 2

Map of the Bruce Dispersion Climatology Study Area

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The area surrounding the facility is very complex. There are wooded areas within about 5 km of the lake. Beyond this is a sharp-rise cliff about 100 m in elevation with a slope of approximately 45°. The land surface above the cliff is generally flat with occasional rolling landscape. The shoreline covers the north, west and south boundaries of the facility. There is no particular wind direction normal to or parallel to the shore. This results in a wide range of onshore flow situations in the Bruce area.

Earlier climatological studies at Douglas Point by Munn and Richards (1963) and Munn (1964) disclosed that the uneven terrain feature of the Bruce area has significant effects on the local air flow pattern. McMillan and Djurfors (1974) and Kiely (1975) also pointed out that a substantial difference in wind profiles at different sites was observed quite frequently at Bruce. Even at a single site, changes in wind direction from level to level were very large, especially during onshore flow situations. These may be attributed to the shoreline and terrain effects.

Onshore flows at Bruce can be generated by synoptic weather systems and by local lake breezes due to surface temperature gradients between the land and lake. The breezes are particularly evident under light synoptic gradient wind conditions. The onshore winds will normally veer (turning clockwise) with height because of surface friction and the effect of the Coriolis force.

The onshore flow pattern would be complicated upon encountering the cliff. Figure 3 displays a schematic picture expected to occur in the Bruce area for an onshore flow situation. When the air moves inland, it may slow down near the surface. Upon reaching the cliff, the air would move upward, following the slope of the cliff. A so-called "surface of separation" may develop on the top of the cliff. The upslope wind will merge with the main air flow and accelerate above the surface of separation. Below that surface, a turbulent wake with counter-flows may be evident. However, the wake and the surface of separation may occur only in a fairly narrow region at the edge of the cliff. At larger distances inland from the cliff, the air flow will adjust to the local surface condition and may have a profile such as would be expected over flat terrain.

It is also possible that a stagnant zone or a cavity with counter-flows forms at the base of the cliff. The size and intensity of this stagnant zone depend on the prevailing wind speed. Downslope winds may occur at night and during the offshore flow situations.

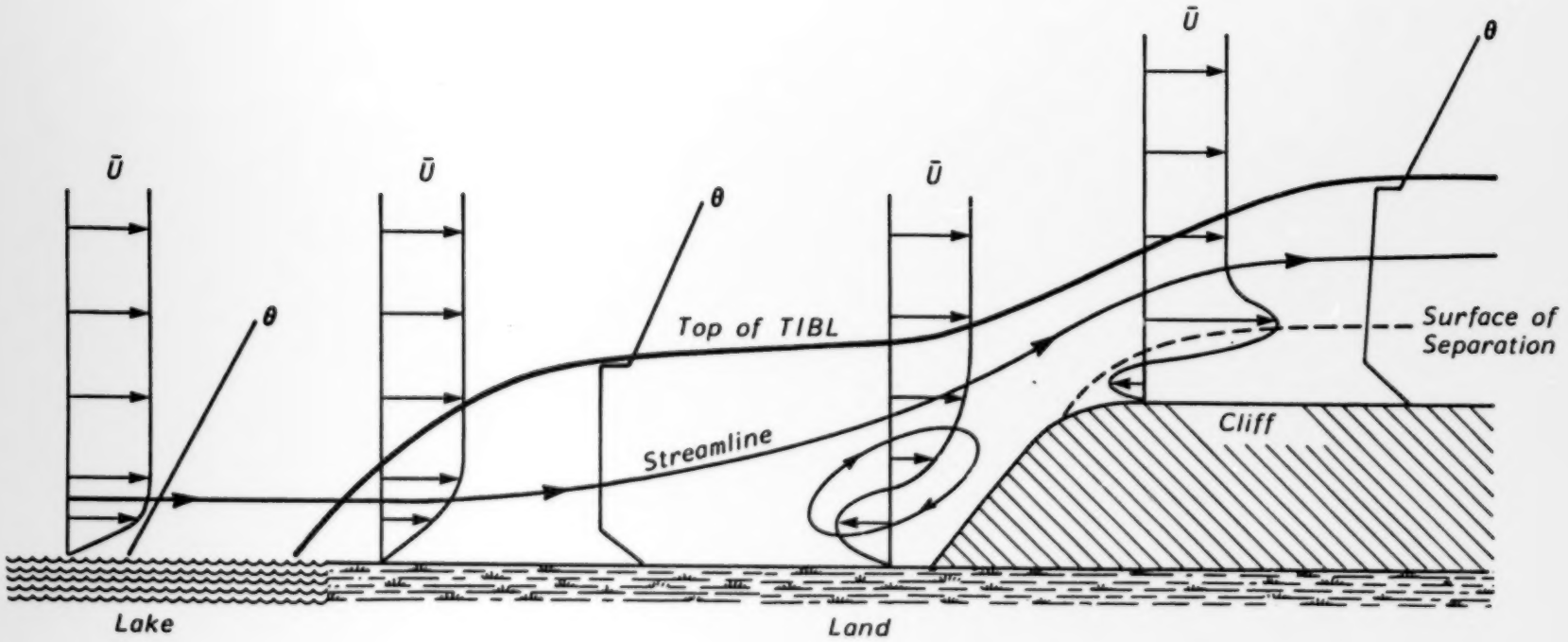


FIGURE 3

A Schematic Picture of an
Onshore Flow Pattern in the Bruce Area

The differential surface temperature between the land and lake may induce the development of a thermal internal boundary layer (TIBL) over land when the land is warmer than the lake and a convective layer over the lake when the reverse is true. Both the TIBL's and convective layers are unstable with turbulent mixing generated by thermal buoyancy. Thus, their development play important roles in determining the dispersion of air pollutants.

Recall that emissions at BNPD are expected to be released from both high-level and low-level sources. In conjunction with the complicated terrain feature and atmospheric structure, the behaviour of such emissions would be very complex. The following is a qualitative description of dispersion characteristics expected to occur at Bruce, based on the description given by Misra (1980).

During the formation of a TIBL, the low-level emissions are expected to be trapped within the mixed layer. A phenomenon known as looping may be observed under this situation. The high-level emissions, on the other hand, may travel first in a stable atmosphere with little dispersion and then intersect the TIBL at a downwind location. The pollutant plume could be fumigated to ground. Both the plume looping and fumigation would lead to relatively high ground-level concentration of pollutants.

During winter, plume dispersion for onshore winds would proceed in a convective wake. The low-level emissions would disperse in a relatively stable atmosphere and exhibit a classic fanning plume behaviour. The high-level emissions may undergo looping close to the source and lofting at greater downwind distances. Neither the plume fanning nor lofting would produce high ground-level concentrations. However, a high ground-level concentration may be observed on the slope area when the fanning plume intersects the cliff. The emissions may be re-circulated back to the station area by downslope flows. They may also be transported to the top of the cliff or dispersed laterally.

During lake-breeze circulation, pollutants from high-level and low-level sources would be caught in the updraft of the lake-breeze front and transported offshore toward the lake. Over the lake, the pollutants may subside in the downdraft of the circulation and produce higher than normal concentrations at the lake surface. Some of the pollutants may be absorbed by the water while others may be carried back to land by the lake breezes.

Trapping of the pollutants in the stagnant zone at the base of the cliff may occur on all occasions and produce relatively high ground-level concentrations. Another possible dispersion characteristic at Bruce is that in which the low-level emissions are trapped beneath the forest canopy in the area surrounding the facility. However, the effect and consequences of this trapping are not known at present.

The above description suggests that the dispersion of air pollutants at Bruce can be impressively complicated. More comprehensive discussions need detailed meteorological information. Accordingly, the objectives of the present study were:

(1) to collect one year of local meteorological data in the Bruce area,

(2) to analyze the data for frequency of occurrence of meteorological parameters which are important to dispersion,

(3) to confirm the above-mentioned lake-induced dispersion characteristics based on the analysis, and

(4) to investigate the lake breeze at Bruce in some detail.

2.0 EXPERIMENTAL DESCRIPTION

2.1 Site Location

The basic objectives of the present study were to collect local meteorological data and use these data to identify some aspects of the dispersion characteristics in the Bruce area. To accomplish this, it is desirable to have an array with enough monitoring sites to provide a sufficiently fine horizontal spatial resolution. However, due to constraints on available instrumentation, only two sites (in addition to the existing Bruce meteorological tower) could be set up for the present study.

Dispersion conditions of greatest interest are usually those associated with onshore air flow. Figure 3 further indicates that the cliff is an important local topographical feature in the Bruce area. In order to take into account these factors in designing the observational network, one monitoring site was located midway between the shoreline and the cliff. Another site was located on the plateau beyond the cliff. These two sites are indicated in Figure 2 as A and B.

More specifically, Site A was located at the Construction Camp area which is about 1.0 km inland from the nearest shoreline. The surrounding area is mainly bare soil with some trees about 10 m in height. This site is further referred to as the Station Site. Site B was located within the Bruce Visitors Information Centre property. It is about 4.0 km inland from the lake on the top of the cliff. The surrounding area is open farmland except the Bruce Information Centre Building which was about 150 m away from the meteorological station. This site is referred to as the Information Centre Site.

It should be noted that these two sites and tne existing Bruce meteorological tower are nearly along a straight line. Thus,

under favourable conditions, the structure of the lower atmosphere before and after the flow is modified by local topography can be determined with this network design.

2.2 Instrumentation

The Atmospheric Research Section has three acoustic sounders, one each of the monostatic, bistatic and Doppler type. The monostatic and bistatic systems are AeroVironment Model 300C and the Doppler system is a Radian Echosonde III. The Atmospheric Research Section also has two Bendix-Freiz anemometers and two CSIRO Funk-Model net pyrradiometers. Except for the Doppler acoustic sounder system, all these instruments were installed in the Bruce area for the present study.

An acoustic sounder is a remote sensing device which uses the scattering characteristics of sound waves from fluctuations in the atmosphere to detect atmospheric thermal and mechanical structures. Detailed descriptions of the principles of the acoustic sounder measurements and their interpretation have been given in several references. Examples are Russell et al (1974); Brown and Hall (1978) and Tam (1983). Thus, only a brief description of the methodology of data interpretation is presented here.

The acoustic sounder consists of a transmitter, a receiver and an output display unit. A pulse of sound is transmitted into the atmosphere, and the intensity of sound reflected back to the receiver is measured as a function of height. These received signals are displayed in facsimile form on a height-time diagram. Acoustic backscattering is caused by small-scale temperature inhomogeneities (the gradients of potential temperature). Typical combinations of turbulence and temperature gradients produce two major types of acoustic echoes, the layer type and the spike type. Generally, the layer echoes indicate weak vertical mixing, or a stable atmosphere, and the spike echoes indicate strong vertical mixing, or an unstable atmosphere. The absence of acoustic echoes represents neutral or very slightly stable atmospheres.

In the case of the monostatic system, the antenna serves both as a transmitter and a receiver. On the other hand, a bistatic system encompasses the basic monostatic components and an additional transmitting antenna to emit a fan-beamed acoustic signal located approximately 150 m away. This enables the bistatic system to measure both the thermal and friction-induced wind fluctuations. In the present study, the bistatic acoustic system was installed at the Station Site and the monostatic system was installed at the Information Centre Site.

The Bendix-Freiz anemometer is a propeller-type anemometer. The wind speeds are determined by the rate of rotation of the propellers and the wind directions are determined by the vane which is designed to continually orient itself into the wind.

The CSIRO Funk-Model pyrradiometer is of the polyethylene dome type. The upper and lower faces of the sensing element are covered by a thin hemispheric dome for protection and to equalize the convective heat exchange between the domes. The net radiation is then determined from the temperature difference across the sensing element, and this is proportional to the difference between the total incoming and outgoing radiation fluxes at all wavelengths. In the field, the instrument is aligned parallel to the ground surface and pointed to the south to ensure the measurement of net radiation from above and below the sensing element.

Additionally, the surface temperatures were measured with Rustrak thermographs. The Rustrak thermograph is a Bourdon tube thermometer which makes use of the differential expansion of some organic fluids, such as glycerin, xylene or alcohol with respect to temperature. In the present study, the Rustrak thermographs were operated and maintained by the Thermal and Hydraulic Generation Division of Ontario Hydro. The unabstracted data were forwarded to us on a tri-weekly basis.

The recorders for these instruments were housed in two mobile trailers situated at the two sites. The anemometer was mounted at the 10-m level of a portable tower which was attached to the trailer. The thermographs were placed in Stevenson screen shelters, at about 1 m above the ground. A summary of the location and types of instruments used at each site is given in Table I.

Wind and temperature data were also collected at the existing meteorological tower which is located at the shoreline near the Bruce NGS A outfall channel area. The data were abstracted by the Ontario Ministry of the Environment and forwarded to the Design and Development Division of Ontario Hydro.

3.0 RESULTS

3.1 Method of Analysis

The principal meteorological variables that influence the dispersion characteristics at the lakeshore environment are wind velocities, atmospheric stabilities, the height of mixed layers, the formation of thermal internal boundary layers and the development of lake-breeze circulations. Dispersion conditions of greatest interest are usually those associated with onshore flow situations. Therefore, the "first cut" analysis involved determining the frequency of occurrence of onshore flow situations based on the available observed data at Bruce.

The onshore flow situation at Bruce was defined as that when surface wind directions were between southwest (225^{o}) and north-northwest (337^{o}) and the wind prevailed a minimum of four hours, during the daytime. When such an onshore flow day was

TABLE I

THE LOCATION AND TYPES OF INSTRUMENTS USED
DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY

Site	Station	Information Centre
Location	Construction Camp	Bruce Visitors Information Centre
Direction from Bruce NGS A	165°	150°
Distance from Bruce NGS A	1.0 km	3.5 km
Types of Instruments	Bistatic Acoustic Sounder Net Pyrradiometer Bendix-Freiz Anemometer Rustrak Thermography	Monostatic Acoustic Sounder Net Pyrradiometer Bendix-Freiz Anemometer Rustrak Thermography

identified, the frequencies of occurrence of other meteorological variables, as mentioned before, were then analyzed. Lake breezes at Bruce were studied in more detail as will be discussed.

3.2 Data Recovery Rate

The instruments at both monitoring sites were operated continuously from July, 1984 to June, 1985. Table II gives a summary of the monthly data recovery rate during the study period. Major data losses occurred as follows:

(1) Poor acoustic sounder data recovery rates at both sites in December, 1984 and January, 1985 were due to a power outage caused by a severe weather storm.

(2) Acoustic sounder data losses at the Information Centre Site in August, September, October and November, 1984 were due to mechanical problems with the display unit.

(3) Poor wind data recovery rates at both sites in December, 1984 and January, 1985 were due to a power outage caused by a severe weather storm.

(4) Wind data losses at the Station Site in April and May, 1985 were due to mechanical failure of the recorder.

(5) Wind data losses at the Information Centre Site in October, 1984 and February, 1985 were attributed to mechanical problems with the Bendix-Freiz anemometer. The instrument was brought back to the Research laboratory for repairs.

(6) Temperature data were not available at either site between December, 1984 and March, 1985. This was due to the limitation of the recorder of the Rustrak thermographs which did not display data below 0 $^{\circ}$C.

(7) Poor temperature data recovery rates in November, 1984 and April, 1985 were due to misalignment of the recording charts.

(8) Solar radiation data were not observed at the Station Site from October to December, 1984 because of the removal of the net pyrradiometer from the site for the Wesleyville tracer study during that period (see Ogram and Edwards, 1985).

(9) Poor solar radiation data recovery rates in December, 1984 and January, 1985 were due to a power outage caused by a severe weather storm.

TABLE II

DATA RECOVERY RATE(%) DURING THE
1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY

Site	Instrument	Jul 84	Aug 84	Sept 84	Oct 84	Nov 84	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	Jun 85	Average
Station	Acoustic Sounder Anemometer	58	100	100	55	73	32	58	100	87	97	100	100	80
	Speed	62	100	95	77	100	36	56	100	100	58	27	99	76
	Direction	52	100	95	76	100	35	56	100	100	100	92	99	84
	Thermography	100	100	100	100	57	0	0	0	0	57	65	100	57
	Pyrradiometer	90	100	67	0	0	0	40	100	100	77	59	99	61
Information Centre	Acoustic Sounder Anemometer	87	16	43	13	57	0	55	54	100	83	74	87	56
	Speed	95	100	99	60	67	48	41	41	95	99	100	99	79
	Direction	95	100	94	44	67	48	41	41	99	99	100	65	74
	Thermography	81	97	77	52	37	0	0	0	0	57	100	100	50
	Pyrradiometer	100	100	100	84	100	45	32	100	100	97	100	100	88

3.3 Statistical Aspects

3.3.1 Wind Velocity

The percentage frequency of occurrence of surface wind directions and the average surface wind speeds by direction at the two monitoring sites during the 1984-1985 study period are presented in Tables III to VI.

As can be seen from Tables III and IV, the prevailing winds at the Station Site were from the south-southwest and south. They accounted for 11.0% and 9.8% of the total winds, respectively. The least frequent winds were those from the northeast (2.3%) and east-northeast (2.4%). On the average, the westerly winds occurred more frequently than the easterly winds. The most frequent winds by month were southwesterly in July, 1984 (21.1%) and south-southwesterly in May, 1985 (19.8%).

The average frequency of calm winds at this site was 10.5% with a higher frequency occurring in the warm months.

The overall average surface wind speed was 9.6 km/h at the Station Site. The westerly winds were stronger than the easterly winds. The strongest winds were from the southwest and west-southwest with an average speed of 14.9 and 14.8 km/h, respectively. The maximum speed was 25.2 km/h from the southwest and was observed in December, 1984. The weakest winds were from the east-northeast with an average speed of 4.9 km/h.

As well, the winds in the cold months were stronger than those in the warm months. The average wind speed in November, 1984 was 13.5 km/h, compared to 5.7 km/h in July, 1984.

Tables V and VI present the wind data observed at the Information Centre Site during the same study period. A slightly more uniform distribution of the winds was seen at this site than at the Station Site. The prevailing winds were from the northwest and north-northwest, which accounted for 8.8% and 8.1% of the total winds, respectively. The north-northeasterly and east-northeasterly winds were the least frequent winds, and accounted for, respectively, 3.6% and 3.7% of the total wind observations. Again, the westerly winds occurred more frequently than the easterlies. The frequency of calm winds was 2.1%, only 20% of that at the Station site.

The average wind speeds at this site were stronger than those at the Station Site, especially the southerly and easterly components. The overall average wind speed was 13.7 km/h with the highest value of 19.7 km/h from the south-southwest. At this site, the southerly and westerly winds were slightly stronger than the northerly and easterly winds. The maximum monthly speed was 34.6 km/h from the south-southwest, occurring in December, 1984. Further, the winds in the cold months were stronger than those in the warm months.

TABLE III

PERCENTAGE FREQUENCY OF OCCURRENCE (%) OF SURFACE WIND DIRECTIONS AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY

Wind Direction	Jul 84	Aug 84	Sept 84	Oct 84	Nov 84	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	Jun 85	Average
N	6.8	7.4	8.9	9.2	10.8	0.8	13.2	1.9	4.2	5.4	14.7	11.9	7.9
NNE	6.6	12.4	3.7	7.4	3.3	0.4	4.3	1.6	5.2	1.0	3.1	0.6	4.1
NE	1.6	2.7	3.1	3.5	2.6	0	2.8	1.8	3.9	1.8	3.4	0.4	2.3
ENE	0.5	2.0	0.7	3.9	0	0	1.7	5.7	7.1	3.5	2.3	1.1	2.4
E	1.1	1.2	1.7	7.8	1.1	0	0.9	3.9	8.2	5.2	1.8	1.8	2.9
ESE	1.4	0.9	3.5	7.1	0	2.3	3.1	3.9	3.1	4.0	3.9	2.8	3.0
SE	0	2.3	5.8	12.4	2.8	8.4	2.2	1.3	2.5	4.6	4.2	1.8	4.0
SSE	0.3	1.1	6.9	5.2	13.2	9.2	3.1	3.9	3.7	5.1	3.8	3.8	5.0
S	7.7	6.5	11.4	5.7	16.3	13.3	9.1	12.2	11.3	10.8	6.4	6.5	9.8
SSW	12.1	14.7	10.8	4.6	9.5	2.3	4.1	13.0	12.1	18.8	19.8	9.5	11.0
SW	21.1	10.7	8.9	6.0	7.9	7.6	1.7	3.7	7.5	5.6	3.4	7.6	7.6
WSW	5.5	3.4	2.1	1.8	5.3	11.4	7.9	9.5	3.4	2.6	2.3	5.2	5.0
W	3.3	1.6	2.5	0.5	6.0	16.8	8.4	10.6	1.2	4.0	1.9	4.3	5.1
WNW	2.5	2.5	3.9	0.4	6.1	12.6	12.0	4.9	2.4	4.6	3.6	8.1	5.3
NW	9.0	6.1	4.8	4.1	5.0	6.5	9.6	12.2	11.4	10.8	6.9	9.5	8.0
NNW	1.4	3.6	11.7	4.4	8.6	5.0	13.7	3.0	4.3	3.6	6.3	8.7	6.2
CALM	19.1	20.9	9.6	16.0	1.5	3.4	2.2	6.9	8.5	8.6	12.2	16.4	10.4
TOTAL	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE IV

AVERAGE SURFACE WIND SPEED (km/h) BY DIRECTION AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY

Wind Direction	Jul 84	Aug 84	Sept 84	Oct 84	Nov 84	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	June 85	Average
N	7.0	10.2	10.6	8.9	14.4	8.0	19.0	12.5	14.9	11.7	6.5	6.7	10.9
NNE	8.6	9.6	8.5	7.3	20.9	4.0	18.4	12.0	11.4	8.0	1.0	2.3	9.3
NE	3.0	5.7	6.4	3.6	15.2	-	11.7	9.7	7.5	6.8	6.5	1.0	7.0
ENE	1.0	3.3	5.8	4.5	-	-	8.1	5.4	7.2	7.5	2.7	3.4	4.9
E	4.3	3.9	3.7	4.7	4.5	-	2.7	6.4	11.6	7.2	3.0	4.3	5.1
ESE	4.4	5.1	8.4	6.5	-	14.2	5.1	10.2	10.4	10.1	4.9	3.5	7.5
SE	-	4.6	6.2	10.0	12.0	9.1	3.4	4.0	9.8	9.0	5.1	5.7	7.2
SSE	5.0	5.7	8.5	7.5	10.9	6.8	7.6	6.0	7.8	7.1	10.4	8.2	7.6
S	3.2	6.1	10.2	9.0	10.3	8.1	5.6	10.3	11.5	10.0	9.8	8.1	8.5
SSW	5.9	7.6	13.3	13.5	12.9	8.3	5.9	14.7	14.1	16.1	11.7	12.6	11.4
SW	10.5	11.1	13.4	12.6	14.0	25.2	6.8	17.1	16.3	19.0	19.8	13.1	14.9
WSW	8.9	9.2	11.5	14.8	17.6	22.5	16.4	13.6	15.2	16.5	20.0	11.1	14.8
W	7.2	5.7	6.9	11.7	14.3	13.3	14.5	12.1	11.1	14.9	3.0	5.4	10.0
WNW	3.7	5.2	6.6	10.5	15.6	11.2	15.0	10.2	10.7	10.7	4.0	3.9	8.9
NW	8.0	6.0	10.7	11.3	12.5	16.7	14.3	17.7	17.8	16.3	5.0	7.2	12.0
NNW	10.4	8.7	11.0	17.3	14.3	17.5	15.8	15.7	14.7	13.0	4.0	7.1	12.5
AVERAGE	5.7	6.7	8.9	9.6	13.5	12.7	10.6	11.1	12.0	11.5	7.3	6.5	9.6

TABLE V

PERCENTAGE FREQUENCY OF OCCURRENCE (%) OF SURFACE WIND DIRECTIONS AT THE INFORMATION CENTRE SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY

Wind Direction	Jul 84	Aug 84	Sept 84	Oct 84	Nov 84	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	June 85	Average
N	4.7	5.7	3.9	4.6	9.7	0.8	6.5	4.0	3.4	5.3	10.8	9.4	5.7
NNE	2.6	7.0	3.4	4.9	5.2	1.4	2.0	1.5	5.7	3.1	4.3	2.5	3.6
NE	1.6	5.7	4.2	0.9	2.9	6.7	3.9	11.4	5.3	0.7	3.5	1.9	4.1
ENE	1.8	1.1	0.8	4.9	1.0	5.0	3.6	7.7	9.7	2.6	5.2	1.1	3.7
E	1.6	3.2	2.7	8.8	1.6	1.9	3.6	12.8	9.5	1.7	4.0	1.7	4.4
ESE	3.6	5.2	6.7	10.7	1.0	8.6	3.6	5.1	6.5	7.4	3.1	2.7	5.4
SE	8.3	6.7	10.1	16.8	3.3	8.9	6.9	4.0	3.6	8.3	8.2	3.4	7.4
SSE	10.7	6.1	12.2	6.1	17.4	3.1	5.9	2.2	6.4	8.0	6.2	6.1	7.6
S	13.6	13.5	10.3	1.2	12.6	3.1	5.5	2.2	12.0	8.8	6.3	4.6	7.8
SSW	11.5	8.6	8.5	4.0	6.8	6.9	2.6	2.2	5.5	11.5	8.1	4.6	6.7
SW	11.5	8.2	5.5	2.7	4.8	6.7	3.3	3.3	7.5	9.5	9.7	3.8	6.4
WSW	2.8	2.8	4.9	3.4	7.3	15.0	8.8	12.4	4.3	6.7	5.2	4.4	6.5
W	5.2	3.5	2.7	1.2	7.5	12.2	18.0	9.5	2.1	3.5	3.6	8.2	6.4
WNW	4.4	3.9	2.7	1.5	5.6	7.5	8.2	5.5	4.0	5.6	1.9	13.0	5.3
NW	8.3	4.9	11.6	6.4	2.5	7.5	10.1	14.7	11.8	8.5	5.5	13.8	8.8
NNW	4.4	8.9	9.7	13.7	8.9	1.6	7.2	1.5	2.7	8.4	14.1	15.9	8.1
CALM	3.4	5.0	0.1	8.2	1.9	3.1	0.3	0	0	0.4	0.3	2.9	2.1
AVERAGE	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE VI

AVERAGE SURFACE WIND SPEED (km/h) BY DIRECTION AT THE INFORMATION CENTRE SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY

Wind Direction	Jul 84	Aug 84	Sept 84	Oct 84	Nov 84	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	June 85	Average
N	6.3	11.6	6.7	6.3	14.4	12.0	14.3	11.3	14.5	10.3	9.4	8.9	10.5
NNE	4.9	8.5	9.4	5.0	19.2	7.8	14.5	7.3	12.0	5.5	6.3	5.0	8.8
NE	3.8	8.7	9.6	9.0	18.9	13.9	19.3	14.7	17.0	4.8	6.2	4.7	10.9
ENE	7.3	6.9	9.8	8.9	13.6	17.5	32.7	14.7	16.8	7.7	10.6	4.8	12.6
E	6.7	6.4	13.9	14.9	10.8	25.1	16.7	23.5	20.8	13.3	11.0	7.3	14.2
ESE	6.6	8.8	12.0	13.7	7.6	22.1	18.4	14.2	25.6	16.7	11.7	12.9	14.2
SE	8.7	9.4	15.6	16.6	14.0	16.9	17.1	9.4	17.2	21.2	16.9	12.9	14.7
SSE	10.4	12.6	17.5	13.7	23.0	14.2	16.4	7.7	18.5	16.1	17.0	13.5	15.1
S	13.6	15.3	18.7	9.5	21.7	22.5	15.1	18.2	23.8	13.5	14.6	12.5	16.6
SSW	13.7	15.1	21.5	20.3	22.0	34.6	16.4	22.0	19.4	17.4	17.8	16.0	19.7
SW	10.7	14.1	14.4	17.7	16.9	23.4	13.5	18.3	15.2	11.3	13.9	11.1	15.0
WSW	8.4	9.0	10.3	19.2	21.3	18.1	15.9	12.9	14.9	9.0	9.3	8.9	13.1
W	12.2	8.9	10.1	11.5	20.6	17.7	16.6	11.7	11.8	13.3	12.7	10.9	13.2
WNW	9.3	7.4	10.5	13.2	19.9	14.6	17.2	18.8	17.6	17.4	11.3	13.9	14.3
NW	9.2	9.4	13.3	18.9	12.8	11.2	19.5	19.8	19.3	20.6	11.8	12.5	14.9
NNW	6.7	10.2	11.0	9.5	15.2	7.2	19.6	10.8	14.3	18.3	11.6	12.4	12.2
AVERAGE	8.7	10.1	12.8	13.0	17.0	17.4	17.7	14.7	17.4	13.5	12.0	9.7	13.7

The combined frequencies of onshore winds at the Station Site and the Information Centre Site were 37.2% and 41.5%, respectively. The average speed of the onshore winds at the Station Site was 12.2 km/h, which is 27% stronger than the overall average of 9.6 km/h. On the other hand, the average speed of the onshore winds at the Information Centre Site was 13.8 km/h, equal to the overall average value. This stronger onshore wind speed at the Information Centre Site may be the result of the merging upslope winds and the main air flow.

Further examination of the wind data reveals that there were 130 days at the Station Site and 107 days at the Information Centre Site in which surface winds were within the onshore flow range and the winds persisted for at least 4 hours during the day time. The monthly distributions of these onshore flow days are given in Table VII. Among these days, 75 days experienced onshore flows at both monitoring sites. Some of these 75 days will be studied in more detail later when the lake-breeze phenomenon is discussed.

3.3.2 Inversions

Information on inversions in the Bruce area was derived from acoustic sounder data. Tables VIII and IX present the percentage frequencies of occurrence of surface-based and elevated inversions at the Station Site during the study period on the onshore flow days. The average depth of surface-based inversions and the average height of the base and depth of elevated inversions are given in Tables X to XII.

It can be seen that the surface-based inversions occurred more frequently in summer and fall than in winter and spring. The highest frequencies of occurrence were 68.8% in October, 1984 and 67.2% in July, 1984. The lowest frequency was 28.7% in February, 1985. The diurnal distributions of the frequency of occurrence were quite similar for all months. The highest frequency was observed during the nighttime and early morning hours. This is associated with the nocturnal radiation cooling at the surface. The lowest frequency was observed during midday.

The monthly average depths of the surface-based inversions were larger in summer and fall than in winter and spring, as shown in Table X. The maximum depth of 205 m was observed in July, 1984. The minimum depth of 75 m was observed in December, 1984. The diurnal distribution of the average depth was, in general, similar to that of the frequency of occurrence. The depth was large in the morning, decreased as the day progressed, to a minimum value in the afternoon and, thereafter, increased again.

The frequency of occurrence of elevated inversions was much less than that of surface-based inversions. As shown in Table IX, the elevated inversions occurred more frequently in fall and winter than in spring and summer. The highest frecuency of

TABLE VII

THE MONTHLY DISTRIBUTION OF THE ONSHORE FLOW DAYS AND POTENTIAL LAKE-BREEZE DAYS DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY

	Jul 84	Aug 84	Sept 84	Oct 84	Nov 84	Dec 84	Jan 85	Feb 85	Mar 85	Apr 85	May 85	June 85	Total
Station Site													
Onshore	11	15	12	5	11	8	12	13	10	11	7	15	130
Lake Breeze	4	13	4	2	0	0	0	0	0	2	4	6	35
Information Centre Site													
Onshore	11	11	9	3	6	8	8	5	10	14	10	12	107
Lake Breeze	4	6	3	1	0	0	0	0	0	5	3	4	26

TABLE VIII

PERCENTAGE FREQUENCY OF OCCURRENCE (%) OF SURFACE-BASED INVERSIONS AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Total
Jul 84	3.4	3.4	3.4	3.8	3.8	3.8	3.8	2.3	1.9	1.9	1.9	1.9	1.5	1.5	1.5	1.9	1.9	1.9	2.3	3.0	4.2	4.2	4.2	3.8	67.2
Aug 84	3.6	3.6	3.6	3.9	3.9	3.9	3.3	1.7	1.1	0.6	0.6	0.6	0.8	0.8	0.8	0.6	0.6	0.8	1.7	3.1	3.3	3.9	3.9	3.9	54.6
Sept 84	2.4	2.4	2.4	2.4	2.8	2.8	3.1	2.0	0.7	0.7	1.0	0.7	0.7	1.0	1.0	1.4	1.4	1.7	2.8	3.8	3.5	3.5	3.5	3.5	51.2
Oct 84	4.2	4.2	4.2	4.2	4.2	4.2	4.2	3.1	2.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	2.1	3.1	4.2	4.2	4.2	4.2	4.2	68.8
Nov 84	3.3	3.3	3.3	3.3	3.3	3.3	3.3	1.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	1.7	2.5	3.3	4.2	4.2	4.2	4.2	4.2	59.7
Dec 84	4.2	4.2	4.2	4.2	3.1	3.1	3.1	3.1	3.1	2.1	2.1	1.0	1.0	1.0	1.0	1.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	66.3
Jan 85	1.7	1.7	1.7	1.7	1.7	1.7	0.8	1.7	1.7	0.8	0.8	0.8	0.8	0.8			2.5	2.5	3.3	3.3	3.3	3.3	3.3	3.3	43.2
Feb 85	0.7	0.7	0.7	1.4	1.4	1.4	1.4	1.4	1.4	0.7	0.7	0.7	0.7	0.7					1.4	2.1	2.8	2.8	2.8	2.8	28.7
Mar 85	2.9	3.3	4.2	4.2	4.2	4.2	3.7	2.1	1.2	0.8									0.8	1.7	1.7	2.1	2.1	2.1	41.3
Apr 85	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1.7											0.4	2.5	3.7	3.7	3.7	3.7	36.9
May 85	2.8	2.8	3.5	3.5	3.5	3.5	2.8								0.7	0.7	0.7	0.7	2.1	3.5	4.2	4.2	4.2	3.5	40.4
June 85	3.0	3.0	3.0	3.6	3.6	3.6	3.0	2.4	0.6									0.6	1.8	3.0	3.0	3.0	3.6	3.6	44.4
TOTAL	34.7	35.1	36.7	38.7	38.0	39.0	35.0	23.2	14.6	9.4	8.9	7.5	7.3	7.6	6.8	7.4	12.9	15.9	26.1	37.5	41.2	42.2	42.8	41.7	

TABLE IX

PERCENTAGE FREQUENCY OF OCCURRENCE (%) OF ELEVATED INVERSIONS AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Total
Jul 84		0.4	0.8	0.8	0.8	0.4	0.4	0.4	0.4		0.4	0.4	0.4	0.4	0.4	0.4		0.4	0.4	0.4	0.4	0.4	0.4		9.2
Aug 84								1.1	0.3	0.6	0.3							0.8	0.3	0.3	0.3				4.0
Sept 84	0.3	0.3	0.7	0.7	0.7				0.3	0.3	0.3	0.7	0.3	0.3	0.3				0.3	0.7	0.7	1.0	1.0		8.9
Oct 84	1.0	1.0	1.0	1.0	1.0	1.0											1.0	1.0	1.0	1.0					10.0
Nov 84		0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8				0.8	0.8	16.0
Dec 84	1.0	1.0	1.0	1.0															2.1	2.1	2.1	2.1	2.1	2.1	16.6
Jan 85			0.8	0.8	0.8	0.8	0.8			0.8	0.8														5.6
Feb 85																									
Mar 85								0.4	0.8	1.2	1.2	0.8	0.8	0.8	0.8										6.8
Apr 85	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4																3.6
May 85				0.7	0.7	0.7	0.7	1.4	0.7													0.7	0.7	0.7	7.0
June 85	0.6	0.6	0.6	0.6	0.6															0.6	0.6	0.6	0.6	0.6	6.0
TOTAL	3.3	4.5	6.1	6.8	5.8	4.1	3.1	4.5	3.7	3.7	3.8	2.7	2.3	2.3	2.3	1.2	1.8	3.0	4.9	4.1	4.1	4.8	5.6	4.2	

TABLE X

AVERAGE DEPTH (m) OF SURFACE-BASED INVERSIONS AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVERAGE
Jul 84	180	170	170	180	185	185	175	255	230	235	230	225	230	210	190	220	225	230	250	220	160	160	195	190	205
Aug 84	140	150	160	145	155	175	175	190	185	105	135	160	240	190	200	220	175	130	150	130	120	130	135	145	160
Sept 84	95	85	95	95	105	135	125	140	160	215	240	255	275	210	260	210	230	195	185	120	115	115	115	125	165
Oct 84	155	155	145	140	130	125	120	115	190	300	340	240	170	140	40	40	80	175	160	140	155	170	160	135	155
Nov 84	105	140	135	155	170	165	110	75	70	90	110	140	190	230	200	160	90	190	195	200	195	200	190	185	155
Dec 84	60	65	65	70	65	60	70	75	80	115	110	60	50	50	60	50	80	80	80	90	90	90	90	95	75
Jan 85	185	180	140	120	120	180	140	110	135	80	80	70	60	40			100	120	120	130	155	180	165	170	130
Feb 85	80	70	60	85	105	130	135	150	125	160	160	180	140	160					60	65	95	110	110	100	115
Mar 85	165	150	180	180	160	150	140	120	170	200									175	130	150	125	120	135	155
Apr 85	140	100	135	155	145	125	110	100											120	105	110	115	125	125	125
May 85	205	165	125	150	135	135	150								80	80	80	80	110	130	155	155	145	130	130
June 85	135	145	145	160	155	170	170	165	160									240	135	175	145	130	135	125	155
AVERAGE	138	131	130	136	136	145	135	125	125	125	117	110	113	102	86	82	88	120	145	136	137	140	140	138	145

TABLE XI

AVERAGE HEIGHT (m) OF THE BASE OF ELEVATED INVERSIONS OF THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVERAGE
Jul 84		180	155	175	195	160	50	60	110		60	130	170	150	110	100		250	140	140	180	190	180		145
Aug 84								110	160	195	230							130	60	30	40				120
Sept 84	40	40	105	70	90				90	340	320	220	100	120	120				60	55	65	95	100		120
Oct 84	70	70	70	70	70	70											280	50	100	110					100
Nov 84		290	320	290	280	260	240	260	320	390	490	430	300	320	300	330	330	280	230				140	160	300
Dec 84	100	120	120	100															130	120	100	100	100	100	110
Jan 85			160	150	140	280	280			140	220														195
Feb 85																									
Mar 85								110	155	220	250	200	185	210	185										190
Apr 85	120	160	140	100	120	160	140	120	200																140
May 85				80	80	80	120	165	100													260	180	190	140
June 85	210	260	140	140	120															150	150	180	160	100	165
AVERAGE	108	160	150	130	136	168	166	138	162	257	262	246	189	200	179	215	305	178	120	100	107	165	143	137	155

TABLE XII

AVERAGE DEPTH (m) OF ELEVATED INVERSIONS AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVERAGE
Jul 84		180	185	135	70	80	40	70	70		120	70	100	140	120	90		100	220	180	120	110	60		115
Aug 84								105	110	130	110							80	50	160	110				110
Sept 84	230	160	115	170	90				90	70	80	95	120	160	160				80	60	110	115	150		120
Oct 84	140	130	130	170	170	160											220	380	360	240					210
Nov 84		230	210	210	170	150	190	240	190	170	110	160	230	180	180	170	170	110	60				130	140	170
Dec 84	200	240	180	300															290	270	270	235	280	280	255
Jan 85			60	130	160	100	80			120	70														105
Feb 85																									
Mar 85								110	90	85	155	100	95	95	100										105
Apr 85	120	80	210	170	130	160	180	160	110																150
May 85				110	140	180	280	140	180																140
June 85	50	90	120	180	90															200	250	220	140	120	150
AVERAGE	148	158	151	175	127	138	154	137	120	115	107	106	136	144	140	130	195	167	177	185	172	147	138	157	150

occurrence was 16.6%, occurring in December, 1984. The diurnal variation of the frequency of occurrence was rather uniform, with slightly higher values in the morning hours and at night. However, the average height of the base of these elevated inversions was greater during the daytime hours, as seen in Table XI. The greatest average height of the base occurred in November, 1984 with a value of 300 m.

Table XII presents the average depth of these elevated inversions. The average depth was larger in the morning hours and at night. The largest depth of 255 m occurred in December, 1984. There were relatively few elevated inversions during the daytime. The daytime inversions are probably eroded by thermal convective activity.

3.3.3 Thermal Internal Boundary Layer

Information on the thermal internal boundary layer at Bruce was also derived from acoustic sounder data. Tables XIII and XIV present the percentage frequency of occurrence and the average depth of the TIBL's at the Station Site during the study period on the onshore flow days.

All the TIBL's occurred in the daytime. As expected, the frequency of occurrence was higher in spring and summer than in fall and winter. The summer season also accounted for the longest duration of the occurrence of TIBL's. The highest frequency of occurrence was 46.9% in May, 1985 and the lowest frequency was 12.5% in December, 1984. Diurnally, the highest frequency occurred at noon hour.

The average depth of the TIBL's was rather uniform by season, with slightly larger values in summer and fall than in winter and spring. This may be associated with the intensity of solar radiation. Similar to that of the frequency of occurrence, the average depth of the TIBL's was largest at noon hour.

3.3.4 Summary

The wind data observed at the Station Site indicate that onshore winds occurred approximately 37% of the time during the 1984-1985 study period. The average wind speed of these onshore flows was 12.2 km/h.

During these onshore flow days, 50% of the time had surface-based inversions, and 30% of the time had a TIBL formation. Thus, emissions released at Bruce during this study period would initially disperse in a stable atmosphere. A concentrated fanning plume would be seen. Subsequently, the emissions would be mixed within the mixed layer. Looping plumes have been observed concurrently.

TABLE XIII

PERCENTAGE FREQUENCY OF OCCURRENCE (%) OF THERMAL INTERNAL BOUNDARY LAYERS AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Total
Jul 84								1.5	1.9	1.9	2.3	2.3	2.3	2.3	2.3	2.3	1.5	1.5	1.5	0.4					24.0
Aug 84							0.3	2.2	2.5	2.8	3.1	3.3	3.3	3.1	3.1	3.3	3.3	2.5	1.1	0.6					34.5
Sept 84								1.0	3.1	3.1	3.1	3.1	3.1	3.1	3.1	2.8	2.8	2.1	0.7						31.1
Oct 84								1.0	2.4	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	2.1	1.0						31.0
Nov 84								1.7	2.5	2.5	2.5	2.5	3.3	3.3	3.3	3.3	2.5	1.7	0.8						29.9
Dec 84										1.0	1.0	2.1	2.1	2.1	2.1	2.1									12.5
Jan 85									0.8	1.7	1.7	2.5	2.5	2.5	2.5	2.5									16.7
Feb 85										1.4	1.4	2.1	3.5	4.2	4.2	3.5	0.7	0.7	0.7						22.4
Mar 85								1.2	1.7	2.5	3.3	3.3	3.3	3.3	3.3	2.1	2.1	2.1	0.8						29.0
Apr 85								1.7	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	2.5	0.4					37.6
May 85							0.7	4.2	4.2	4.2	4.2	4.2	4.2	4.2	3.5	3.5	3.5	3.5	2.1	0.7					46.9
June 85							0.6	1.2	3.0	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	1.2						38.4
TOTAL							1.6	15.7	25.1	31.1	32.6	35.4	37.6	38.1	37.4	35.4	26.4	23.1	12.4	2.1					

TABLE XIV

AVERAGE DEPTH (m) OF THERMAL INTERNAL BOUNDARY LAYERS AT THE STATION SITE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Time (hour)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	AVERAGE
Jul 84								140	250	280	265	260	245	255	250	240	240	215	130	70					220
Aug 84							120	120	200	230	250	270	270	265	255	245	225	200	145	140					210
Sept 84								140	140	200	255	285	315	300	270	270	215	155	120						225
Oct 84								130	120	125	150	170	225	275	295	255	230	150	120						190
Nov 84								125	230	285	275	280	235	235	210	200	230	200	230						230
Dec 84										120	260	265	305	290	205	120									225
Jan 85									60	65	95	120	135	150	140	130									115
Feb 85										50	160	145	165	165	145	130	140	120	110						135
Mar 85								140	160	155	185	185	195	200	195	210	180	180	115						175
Apr 85								145	170	215	215	205	195	190	180	175	160	150	120	110					175
May 85							180	160	185	180	185	195	185	185	185	180	160	150	205	180					180
June 85							110	130	150	170	185	205	215	200	195	190	155	125	170						170
AVERAGE							137	137	166	173	207	215	224	226	210	155	194	165	146	125					

Under calm or very light wind conditions (calm conditions accounted for 10% of the time at the Station Site), emissions may have been dispersed evenly in the station vicinity.

3.4 Lake Breezes

The basic mechanism for the generation of lake breezes is horizontal pressure gradient forces. On a calm, clear day, solar radiation heats up a land surface more rapidly than a water surface. The air over the land is warmer and lighter and thus moves upward. The updraft generates a low pressure area on the surface. The air over the lake is then accelerated horizontally toward the land resulting in an onshore flow. This onshore flow further enhances the updraft and forces the updraft zone to penetrate landward. The rising air will cool adiabatically and, because of hydrostatic conditions, the surface low pressure weakens with height and eventually becomes a high pressure area aloft. The air at upper levels will accelerate horizontally toward the lake as a returning flow. This completes a lake breeze circulation.

Thus, the development of a lake breeze depends upon the following factors:

(1) the land-lake surface temperature difference,

(2) the speed and direction of the large-scale gradient wind,

(3) the vertical stability of the lower atmosphere,

(4) the Coriolis force,

(5) the topography of the land surface, and

(6) the curvature of the coastline.

There is no doubt that the lake breezes in the Bruce area occur mostly in the summer months. Wind data observed at the Station Site during the 1984-1985 study period showed that there were 35 days with lake breeze potential. The highest frequency of these days occurred in August, 1984, as shown in Table VII. These potential lake breeze days were defined when the observed surface winds exhibited opposite direction changes during the daytime and an evident increase in speed of the onshore wind direction. Some of these days may not be real lake breeze days because, theoretically, a lake breeze should have a discernible return flow layer aloft and a definite front or convergence zone. However, they cannot be confirmed as lake-breeze days in the present study due to the lack of vertical profile data.

Lake breezes have significant impacts on the dispersion of air pollutants. The lake-breeze circulation is capable of recirculating the pollutants onshore and cause concentrations higher

than would otherwise be expected. Thus, an accurate prediction of a lake breeze has received considerable attention in the field of air pollution meteorology.

In recent years, sophisticated numerical models (eg, McPherson, 1970; Pielke, 1974) have been developed and successfully used to simulate the formation and structure of the breeze circulations, taking into account those factors described before. However, these models were not originally designed for routine operation and their performance depends greatly upon expertise and computer facilities.

Biggs and Graves (1962), on the other hand, used a simple technique, known as a lake-breeze index, to predict whether or not a lake breeze will occur. Their index was defined as the ratio of inertial to buoyancy forces and was given by

$$\text{Lake-Breeze Index} = \frac{V^2}{C_p \Delta T} \qquad (3\text{-}1)$$

where V is the average wind speed (m/s), C_p is the specific heat of dry air at constant pressure (1.003 J/g°K) and ΔT is the difference between the lake and land surface temperatures (K). Biggs and Graves (1962) had applied this index to the western shore area of Lake Erie and reported a critical value of 3.0 for separating lake breeze days and non-lake breeze days with an accuracy of 92%.

Lyons (1972) later modified the index by using surface geostrophic wind and taking into consideration the amount of cloudiness and the direction of large-scale gradient wind with respect to the shoreline. A critical value of 10.0 was found for the Chicago lake breezes.

Examination of the index reveals that a large value of the index is associated with large inertial forces. In other words, the kinetic energy generated by the large-scale gradient wind would overcome the buoyancy generated by differential surface heating. Lake breezes are unlikely to develop under such situations. On the other hand, a small value of the index indicates that the dominating force is buoyancy, a situation favourable for the development of a lake breeze. The critical value of the index to delineate lake breeze days and non-lake breeze days should be site dependent and can be determined from observations.

At Bruce, the midday winds are measured regularly at the Bruce meteorological tower and the Wiarton weather station. The tower is located very close to the shoreline and the Wiarton weather station is located some 60 km to the northeast of the Bruce facility, on the south shore of Georgian Bay. Winds measured at these two locations are highly variable due to the land-lake boundary and their representativeness of the general wind in the

Bruce area needs to be tested. Since the large-scale gradient winds have significant effects on the development of a lake breeze, the geostrophic wind determined from the surface synoptic weather maps may be used as an alternative.

The geostrophic wind may be expressed by

$$Vg = \frac{1}{f\rho} \frac{\delta p}{\partial n} \qquad (3\text{-}2)$$

where f is the Coriolis parameter, ρ is the density of the air, p is the surface pressure and n is the horizontal distance measured normal to the flow. For calculation purposes, $\partial p/\partial n$ is approximated by the finite difference ratio $\frac{\Delta p}{\Delta n}$ in which Δp is 4 mb (customarily used on surface synoptic weather maps) and Δn is the normal distance in meters between two adjacent isobars. Further, a density of 1.187 kg/m^3 (ie, average temperature of 18°C and station pressure of 990 mb) and a latitude of 44.5° N were assumed for the Bruce area. Then, the surface geostrophic wind determined from the synoptic weather maps is written as

$$Vg = 3.31 * 10^6 * (\Delta n)^{-1} \qquad (3\text{-}3)$$

The lake-breeze index for Bruce becomes

$$\text{Lake-Breeze Index} = 1.09 * 10^{13} * (\Delta n^2 \Delta T)^{-1} \qquad (3\text{-}4)$$

Comparison of the temperature data measured at the Station Site and the Bruce meteorological tower illustrated that they were very much identical. Thus, the maximum temperature obtained at the tower may be used for the index calculations. The lake surface temperature is not included in the routine measurements. However, occasional surveys of the surface temperature over Lake Huron, obtained by analyzing satellite images, are available from the Canadian Atmospheric Environment Services. These temperatures may be used since the lake surface generally exhibits little diurnal variation in temperature due to the high thermal capacity of water.

With the above information, the lake-breeze index at Bruce can be calculated. Table XV presents the computed values of the index on all the onshore flow days in potential lake-breeze months during the 1984-1985 study period. The dominant synoptic weather situations on these days are also given in the table.

The observed wind data showed that there were 35 onshore flow days having lake breeze potential. These days are outlined in Table XV with an asterisk next to their date. In view of the synoptic weather situations, the onshore flows on 14 of these 35 days were generated by frontal passages; on three of the days the onshore flows were due to the presence of troughs and cyclones and on another two days negative temperature differences

TABLE XV

LAKE-BREEZE INDEX COMPUTATIONS AT BRUCE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

Date	Land Temp (°C)	Lake Temp (°C)	Isobar Spacing (km)	Wind Speed (km/h)	Lake Breeze Index	Dominant Weather
7-11-84	22	18	800	15	4.2	Front
†*7-12-84	25	18	400	30	9.7	High
7-13-84	29	18	550	22	3.3	High
7=14-84	30	18	750	16	1.6	Front
7-15-84	25	18	300	40	17.3	Front
7-16-84	22	18	350	34	22.3	Front
7-24-84	21	17	250	47	43.7	Front
†*7-25-84	23	17	500	24	7.3	High
†*7-29-84	23	17	500	24	7.3	High
7-30-84	26	17	500	24	4.8	Trough
†*7-31-84	28	17	350	34	8.1	High
*8- 1-84	24	17	600	20	4.3	Front
†*8- 4-84	26	16	500	24	4.4	High
†*8- 5-84	27	16	400	30	6.2	High
*8- 6-84	28	16	500	24	3.6	Front
8- 7-84	24	16	300	40	15.2	Front
*8- 9-84	30	16	700	17	1.6	Front
†*8-14-84	25	16	700	17	2.5	High
†*8-15-84	28	16	400	30	5.7	High
†*8-20-84	23	16	400	30	9.7	High
†*8-21-84	25	16	400	30	7.6	High
8-22-84	22	16	400	30	11.4	Front
†*8-25-84	23	16	700	17	3.2	High
†*8-26-84	27	16	550	22	3.3	High
*8-30-84	22	16	300	40	20.2	Front
†*8-31-84	22	16	450	27	9.0	High
9- 6-84	18	17	600	20	30.3	High
*9-10-84	21	17	300	40	30.3	Front
9-11-84	21	17	600	20	7.6	Front
9-13-84	22	17	200	59	54.6	Front
9-15-84	14	17	400	30	-	Front
*9-16-84	17	17	350	34	-	High
9-19-84	18	16	250	47	87.4	High
9-20-84	20	16	200	59	68.3	Front
*9-23-84	20	16	400	30	17.1	Front
9-26-84	10	16	200	59	-	Front
9-27-84	12	16	400	30	-	High
*9-28-84	14	16	650	18	-	Trough

TABLE XV

LAKE-BREEZE INDEX COMPUTATIONS AT BRUCE DURING THE 1984-1985 BRUCE DISPERSION CLIMATOLOGY STUDY ON THE ONSHORE FLOW DAYS

(cont'd)

Date	Land Temp (°C)	Lake Temp (°C)	Isobar Spacing (km)	Wind Speed (km/h)	Lake Breeze Index	Dominant Weather
*10- 1-84	14	16	900	13	-	High
10- 3-84	15	16	200	59	-	Front
*10- 4-84	13	14	250	47	-	Front
10-17-84	17	14	250	47	87.4	Front
10-26-84	13	12	450	27	53.8	Front
4- 1-85	-6	1	200	59	-	Low
4- 2-85	-2	1	200	59	-	Low
4- 3-85	-6	1	200	59	-	Front
4- 6-85	-2	1	150	79	-	Front
4- 7-85	3	1	150	79	-	Front
4- 8-85	-1	1	600	20	-	Trough
4- 9-85	-3	1	300	40	-	High
* 4-15-85	9	8	500	24	43.7	Front
* 4-16-85	7	8	400	30	-	Trough
4-25-85	18	8	300	40	12.1	Low
4-28-85	18	8	600	20	3.0	High
†* 5- 3-85	18	8	350	34	8.9	High
5- 7-85	18	8	250	47	17.4	Front
* 5-13-85	15	6	300	40	13.5	Front
5-18-85	10	6	400	30	17.1	Trough
5-20-85	15	6	200	59	30.3	Front
†* 5-29-85	20	6	700	17	1.6	High
* 5-31-85	24	6	200	59	15.2	Front
6- 1-85	27	8	150	79	25.5	Low
6- 3-85	21	8	300	40	9.3	Trough
†* 6- 4-85	26	8	300	40	6.7	High
6- 6-85	21	8	600	20	2.3	High
* 6- 9-85	28	8	200	59	13.7	Front
* 6-10-85	23	8	400	30	4.6	Front
6-11-85	16	8	400	30	8.5	Trough
* 6-12-85	19	8	400	30	6.2	Low
6-13-85	17	8	300	40	13.5	Front
6-14-85	18	8	300	40	12.1	Front
6-18-85	17	12	300	40	24.3	Front
* 6-19-85	19	12	200	59	39.0	Front
* 6-20-85	18	12	450	27	9.0	Front
6-24-85	18	14	400	30	17.1	Front
6-25-85	17	16	450	27	53.9	Front

(the lake temperature was warmer than the land surface temperature) were experienced. Thus, only 16 days were real potential lake breeze days during this study period. These 16 days are outlined in Table XV with a dagger next to the asterisk. As seen from the table, the computed values of the lake-breeze index on these 16 days ranged between 1.6 and 9.7. Interestingly, they were all less than the value of 10.

Further manipulation of Equation (3-4) elucidated that an index value of 10 is obtained when Vg = 10 m/s and $\Delta T = 10^{o}C$. This combination more or less satisfies the sufficient conditions for the formation of a lake breeze when the geostrophic wind is from lake to land as described by Defant (1951). The occurrence of this condition is unlikely to be rare in the summer season at Bruce. The value of 10 was also used by Wong (1983) in his analysis of lake-breeze frequency at Bruce in 1982. For preliminary study, the critical value of 10 may be applied to predict lake breeze days and non-lake breeze days in the Bruce area. A more refined, site-representative value could be obtained if vertical observations of the lake breeze were available.

4.0 A CASE STUDY: AUGUST 14-25, 1984

The purpose of this section is to provide an example of the dispersion climatology which occurred in the Bruce area. The case of August 14-15, 1984 was chosen mainly for its relatively complete observational data and the presence of conditions conducive to lake-breeze development.

Figures 4 and 5 display the surface synoptic weather situations at 1200 GMT for August 14 and 15, respectively. On August 14, a low pressure cell was centered over the eastern end of Ontario with a cold front extending southward to the eastern portion of the United States. This cold frontal system had weakened and moved eastward to the Atlantic coast the next day. Thus, it had no adverse effect on the weather over the Great Lakes region.

The weather over the Great Lakes region was under the influence of a high pressure system whose centre was situated over Wisconsin on August 14 and moved to Ohio on August 15. Surface geostrophic winds over the lower Great Lakes were light (17 km/h) from the northwest on August 14 and moderate (30 km/h) from the west on August 15. With fair skies in southern Ontario, these two days presented suitable conditions for a lake-breeze development in the Bruce area. The surface winds observed at the two monitoring sites on these two days are given in Table XVI. It can be seen that calm wind conditions were observed in the early morning and late evening hours on August 14. During the daytime, prevailing winds were northwesterly at both sites. The wind speeds were stronger at the Information Centre Site than at the Station Site. On August 15, the

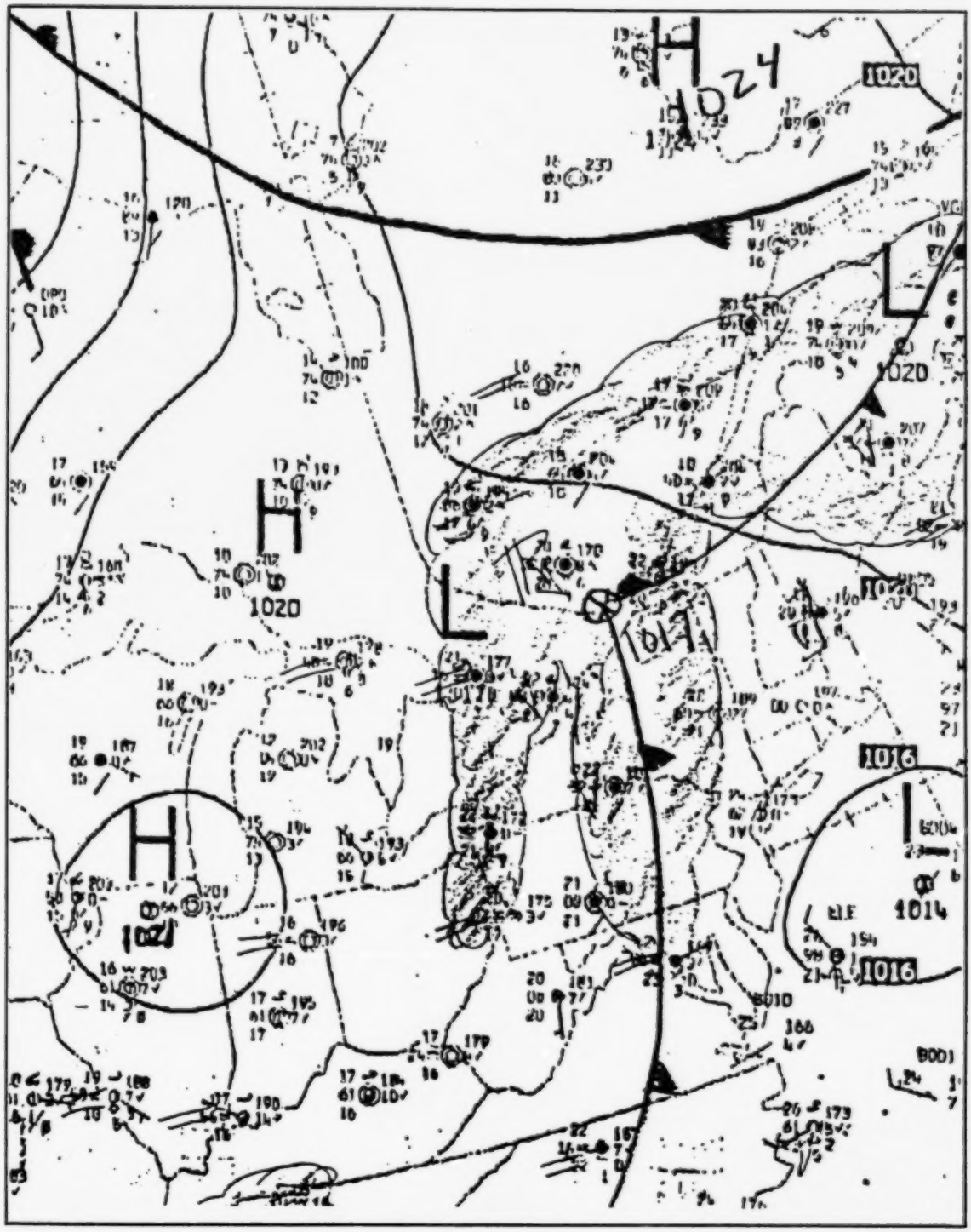


FIGURE 4

Surface Synoptic Weather Map at
1200 GMT for August 14, 1984

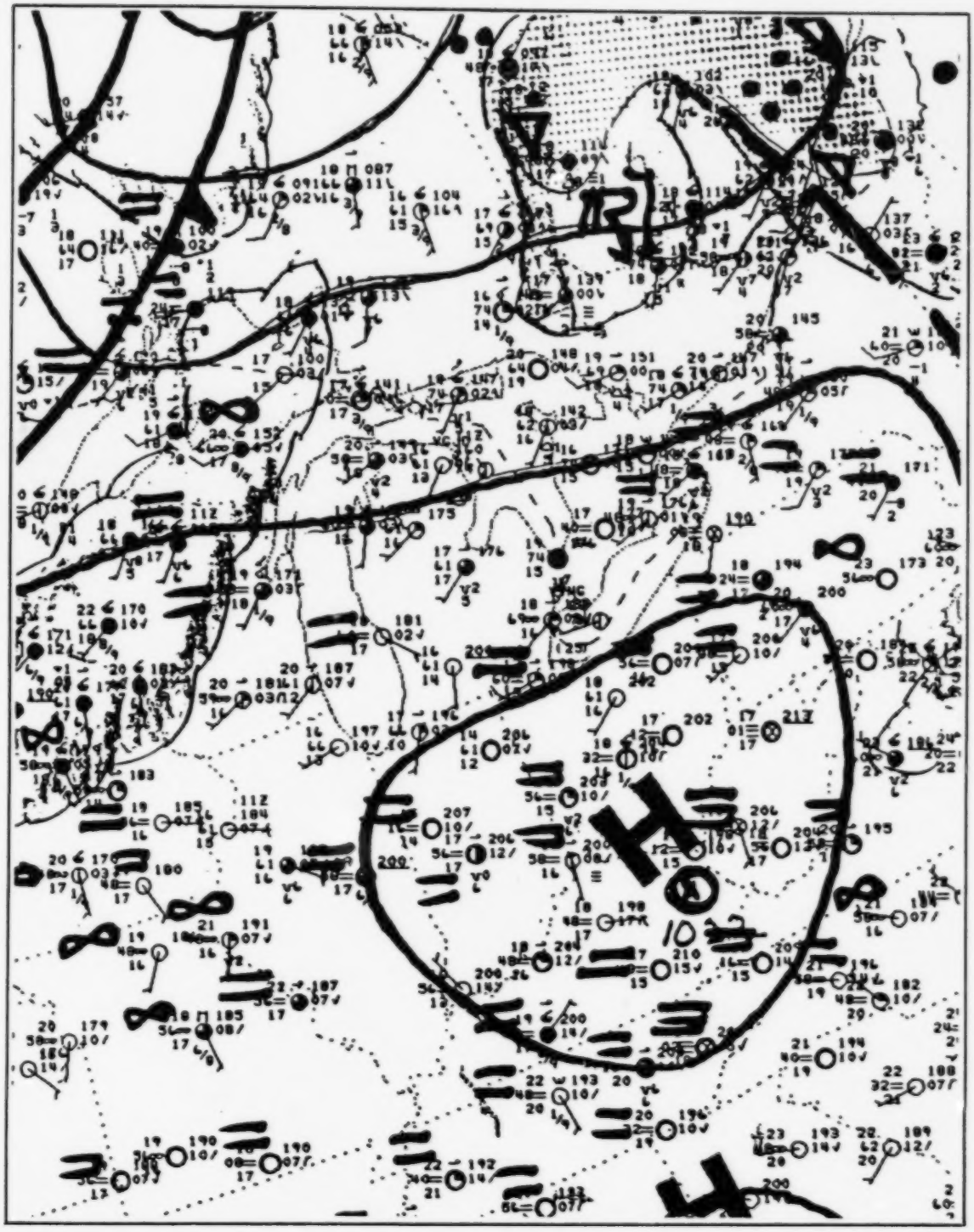


FIGURE 5

Surface Synoptic Weather Map
at 1200 GMT for August 15, 1984

TABLE XVI

SURFACE WIND OBSERVATIONS AT THE STATION AND INFORMATION CENTRE SITES ON AUGUST 14 and 15, 1984

	Station Site				Information Centre Site			
	August 14		August 15		August 14		August 15	
	Speed (km/h)	Dir (from)	Speed (km/h)	Dir (from)	Speed (km/h)	Dir (from)	Speed (km/h)	Dir (from)
0	C	C	C	C	C	C	8	180
1	C	C	C	C	C	C	8	158
2	C	C	C	C	C	C	4	100
3	C	C	C	C	C	C	10	135
4	C	C	C	C	C	C	11	146
5	C	C	2	200	C	C	10	150
6	C	C	5	205	C	C	8	213
7	3	315	6	230	C	C	9	230
8	4	315	8	248	8	303	7	258
9	5	315	11	240	10	325	16	240
10	5	310	15	236	10	303	20	236
11	6	310	16	240	8	280	23	236
12	8	310	16	240	11	295	25	236
13	9	315	15	240	12	295	23	236
14	8	315	15	240	11	303	18	236
15	7	315	14	225	14	315	17	225
16	7	310	16	225	10	303	18	225
17	6	305	11	225	8	295	15	220
18	5	305	10	225	6	315	12	213
19	C	C	10	225	C	C	14	225
20	C	C	8	200	C	C	10	225
21	C	C	6	210	C	C	9	225
22	3	200	5	210	C	C	8	220
23	2	195	5	210	C	C	11	230

prevailing winds were southwesterly. Again, the winds were stronger at the Information Centre Site. Also, the winds were stronger on August 15 than on August 14 at both sites. Note that winds during the daytime hours were within the onshore flow range and the speed increased from the morning to its peak at about midday. The speed decreased thereafter. This is strong evidence that the onshore winds on these two days were, in fact, the lake breeze.

Figures 6 and 7 display the surface temperatures observed on these two days at the two sites. A diurnal variation of surface temperature can be depicted in these figures. Higher temperatures were observed during the daytime with maximum temperatures of 25°C and 28°C on August 14 and August 15, respectively. The distribution of the surface temperature over Lake Huron on August 12, 1984 at 2100 GMT is shown in Figure 8. The average lake surface temperature in the Bruce area was approximately 17°C which was slightly cooler than the mean lake temperature of 19°C. Using these meteorological data, the calculated lake breeze indices for these two days were 2.8 and 6.2, respectively.

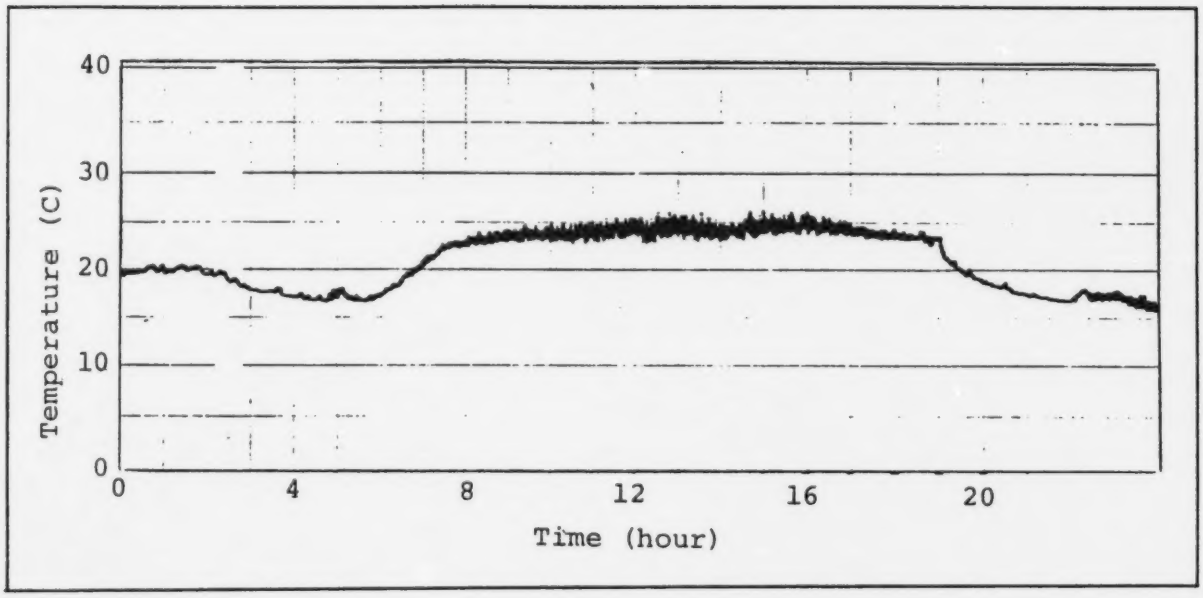
The acoustic sounder data collected at the Station Site on these two days are displayed in Figure 9. A nocturnal stable layer of about 100 m in depth was observed in the early morning hours on both days. This stable layer dissipated gradually by about 0700 EST and eventually was replaced by a convective unstable layer. The depth of the unstable layer was rather uniform with a maximum of 300 m on August 14 and 250 m on August 15. The strength of these unstable layers was moderate, according to the darkness of the spike echoes.

Figure 10 gives the diurnal variations of the net solar radiation on these two days. The maximum net solar radiation was 1.84 MJ m^{-2} on August 14 and 1.98 MJ m^{-2} on August 15. Radiation cooling was observed in the early morning and at night on both days (the ordinate value of 20 represents zero solar radiation).

Based on the above description of the atmospheric conditions, the following dispersion climatology is expected to have occurred on these two days in the Bruce area.

Before dawn on August 14, emissions from both low-level and high-level releases would homogeneously disperse in the atmosphere over the generating station. The dispersion would depend mainly on the properties of the emission itself since calm wind conditions provide no mechanical mixing.

By about 0700 EST, an onshore flow began to develop. Emissions would then travel downwind in the form of a plume. The surface also started to warm up at this time. A mixed layer with a growing rate of about 100 m/h was observed shortly after dawn. This mixed layer reached its maximum depth of about 300 m at



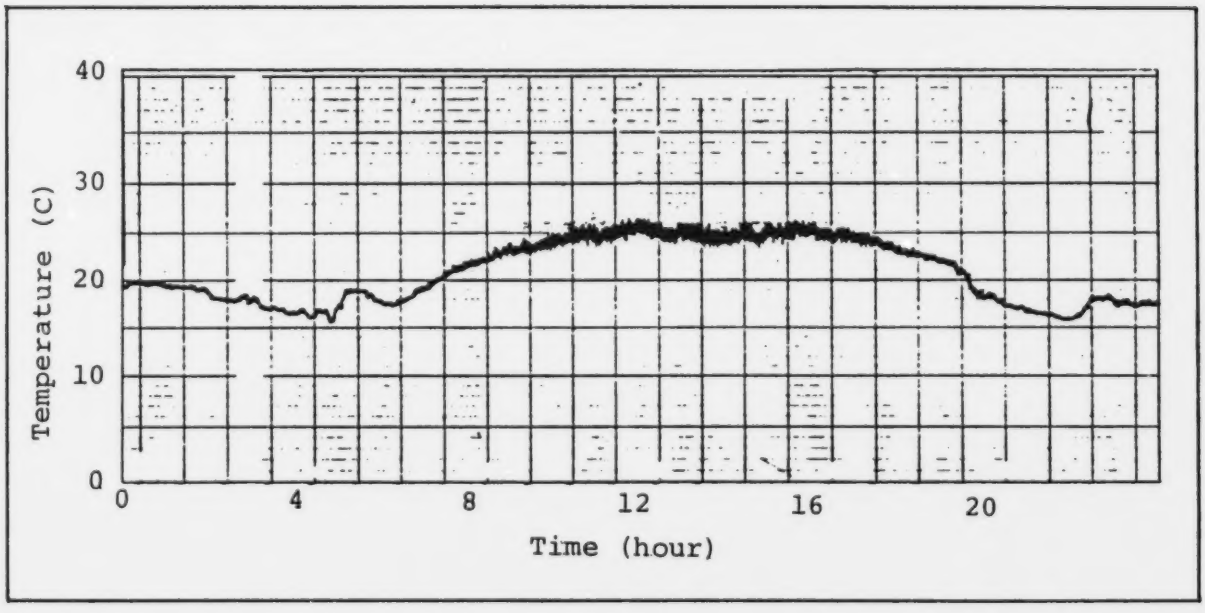


FIGURE 6

Surface Temperature Observed at the Station (Top) and Information Centre (Bottom) Sites on August 14, 1984

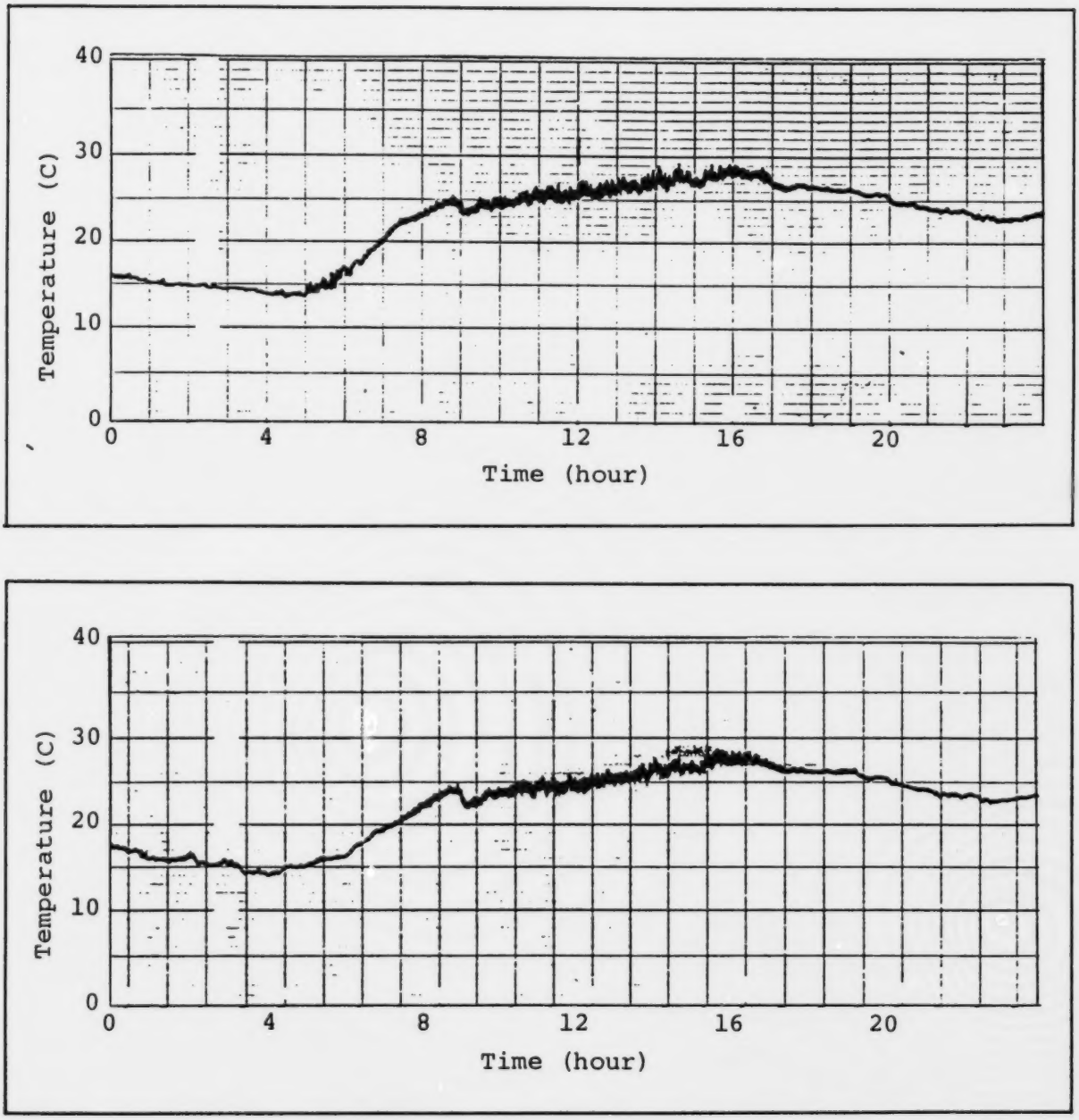


FIGURE 7

Surface Temperature Observed at the Station (Top) and Information Centre (Bottom) Sites on August 15, 1984

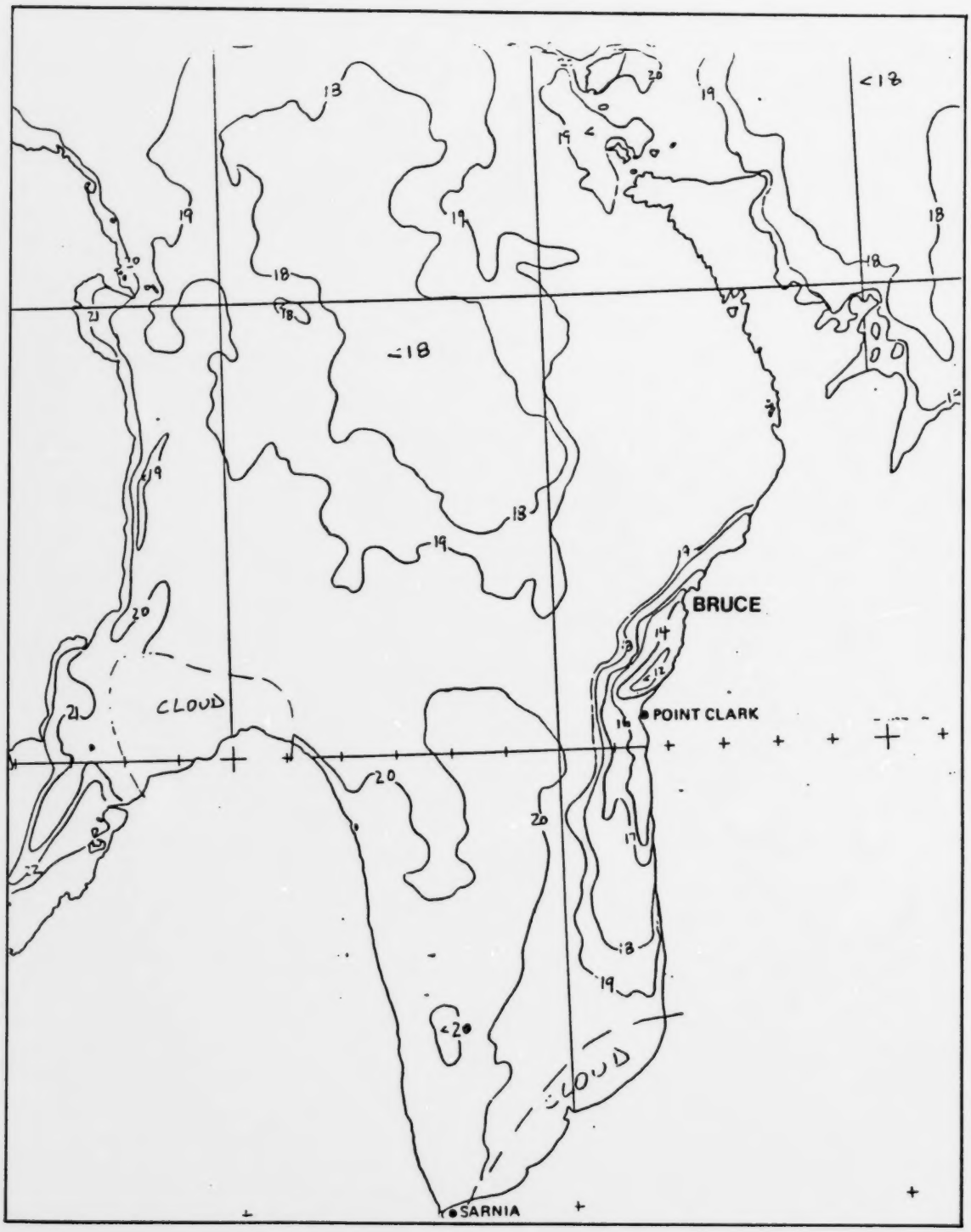


FIGURE 8

The Distribution of Surface Temperature Over Lake Huron on August 12, 1984 at 2100 GMT

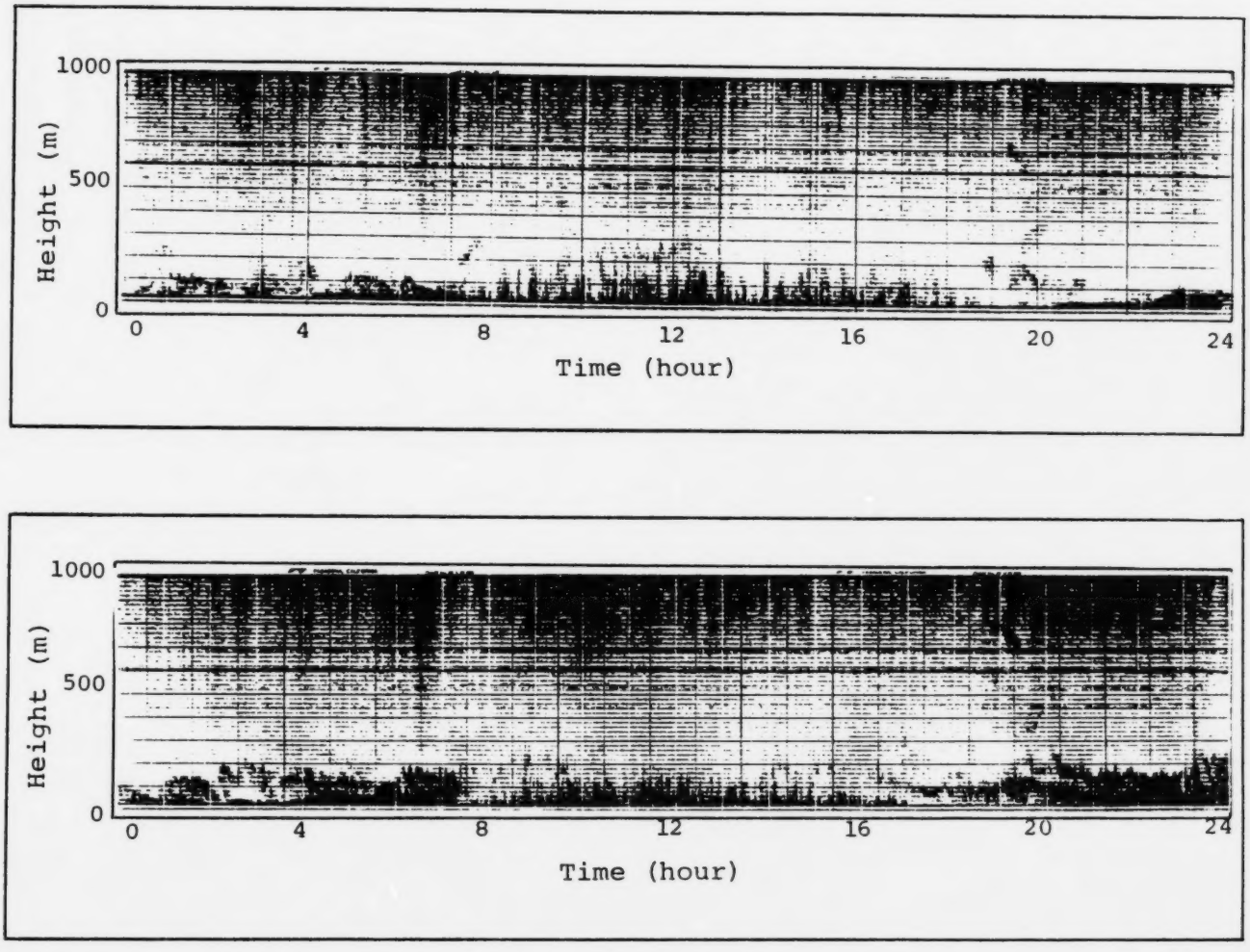
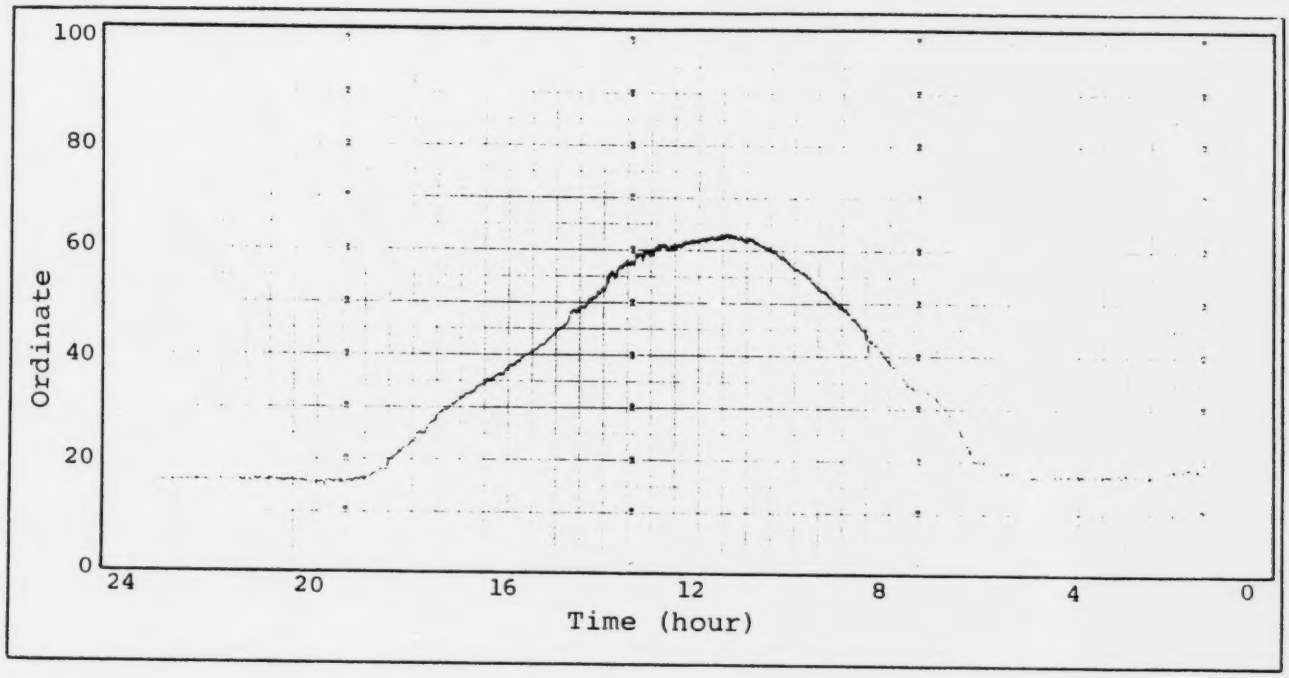


FIGURE 9

Acoustic Sounder Signals Observed on
August 14 (Top) and August 15 (Bottom), 1984



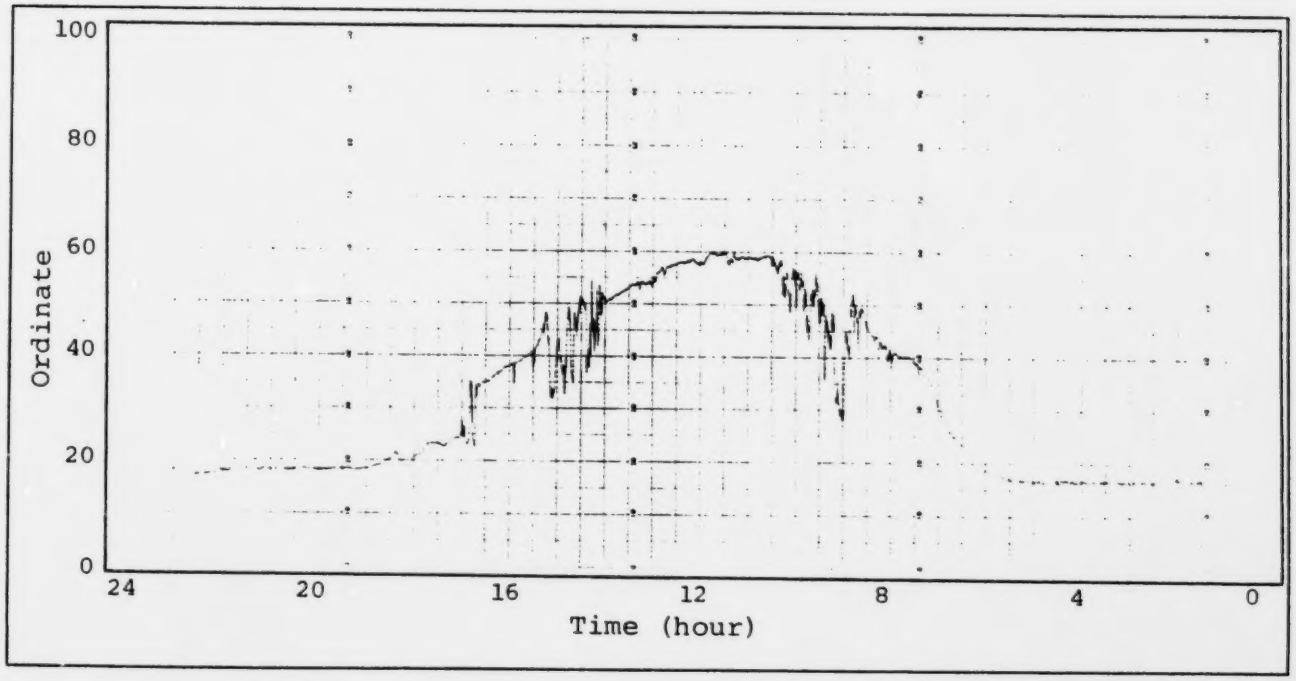


FIGURE 10

Net Radiation Data Observed on
August 14 (Top) and August 15 (Bottom), 1984

1100 EST. Thus, plumes from both low-level and high-level releases would undergo vertical mixing within this mixed layer.

Horizontally, the plume would experience relatively little dilution and spread because the temporal variations of wind direction were small on August 14. As a result, the plume would be narrow and concentrated. As the plume travelled downwind, looping would be expected to occur. Subsequently, instantaneous high ground-level concentrations would be observed in areas below and above the cliff in the downwind direction.

The daytime mixed layer diminished at about 2000 EST and a nocturnal inversion layer began to establish itself. This inversion layer grew to about 100 m in depth by 2200 EST and remained at that depth throughout the night, as shown in the acoustic sounder chart. The nocturnal inversion layer has a blocking characteristic which would prevent the daytime plume from reaching the ground surface. The plume would then disperse upward to the relatively unstable atmosphere aloft.

When the nocturnal inversion was eroded by surface heating in the morning on August 15, the plume would again undergo vertical mixing. As shown in Table XVI, the surface winds on August 15 were veering from south-southwest to southwest. Thus, the plume would disperse to a wider area in the horizontal direction. In conjunction with the vertical mixing, a larger high ground-level concentration zone would be observed on this day.

Moreover, emissions on August 14 would likely have risen to higher levels at the lake-breeze front and would have advected lakeward in the returning flow layer aloft. These emissions would subside to the lower levels over the lake and would be carried onshore on August 15. This process would produce a higher background concentration of emission on August 15 than would otherwise be expected.

In the case of nighttime releases, the low-level emissions would be trapped within the stable layer resulting in a thin and concentrated fanning plume. The high-level emissions would be dispersed in a transition layer between the surface stable layer and the upper unstable layer. The lower segment of the plume would experience little vertical mixing, but it might be dispersed laterally. The upper segment of the plume would exhibit a lofting behaviour and disperse upward.

In summary, meteorological data collected on August 14 and 15, 1984 indicated that these two days were lake-breeze days. The geostrophic winds were light to moderate, skies were clear and the surface heating was obvious. Comparing the data on these two days revealed that the wind speeds and horizontal wind shear were stronger, the temperatures were higher but the depth of the TIBL's was lower on August 15 than on August 14. This translates to larger horizontal turbulence and weaker vertical mixing on August 15 than on August 14.

Therefore, after release, emissions would initially disperse evenly in the atmosphere over the station. Emissions would then travel downwind in the form of a concentrated fanning plume. Looping would likely occur when the land was heated up during the daytime. Nocturnal inversions at night would prevent the daytime plume from reaching the ground. The lake-breeze circulation would produce a higher than normal background concentration of emissions on the second day. Also, a wider horizontal dispersion would be observed on the second day, due to larger wind shear.

The cliff may act as a barrier to the low-level plume. Emissions would be accumulated against the slope of the cliff. Some of the emissions would be moved upward to over the cliff and sideward by the topography-induced flow. Some may return to the station area at the lowest level by drainage and/or downslope flows. However, no general scenario can be given at present.

5.0 CONCLUDING REMARKS

A preliminary study of the dispersion climatology of the Bruce area is described in this report. The study was conducted between July, 1984 and June, 1985. The instrumentation used in this year-long study included one monostatic and one bistatic acoustic sounder, two net pyrradiometers, two anemometers and two thermographs. These instruments were operated at two sites in the Bruce nuclear facility. One site was located at the Construction Camp, midway between the lakeshore and the cliff and another site was located at the Bruce Visitors Information Centre, on top of the cliff.

This instrument package collected data on the thermal structure of the lower atmosphere, the net solar radiation, the surface wind velocity and temperature. Due to a severe weather storm and problems with instrument maintenance, the data recovery rates were not as good as we would wish. Had more frequent site inspections been made, the data recovery rate would have been largely improved.

According to the collected data, onshore flow conditions occurred about 40% of the time. The overall average speed of the onshore winds was 13 km/h. The onshore flows occurred more frequently in the warm months. During the onshore flow days, the atmosphere was stable in the early morning and late evening hours. This was exhibited as the surface-based nocturnal inversion. After sunrise, the stable layer was lifted to higher levels by convective heating. The frequency of occurrence of the surface-based and elevated inversions was 50% and 8%, respectively, at the Station Site. The thermal internal boundary layer was observed on 30% of the daytime onshore hours.

At Bruce, lake breezes occur mostly in the summer months. Lake breezes may occur on up to 21% of the onshore flow days. A simple index, similar to that of Biggs and Graves (1962) and Lyons (1972), was derived to predict lake breeze days and non-lake breeze days. The information needed for the index calculation includes the geostrophic wind, determined from surface synoptic weather maps, and the difference between the lake and land surface temperatures in the Bruce area. The computed values of the index were less than 10 on those days with lake breeze potential.

A case was discussed in terms of the local meteorological conditions and the likely behaviour of low-level and high-level emissions. It was postulated that the emissions released in this case would travel downwind in the form of a fanning, concentrated plume. Because of the local topographical features, emissions would be accumulated at the base of the cliff, especially at night. While above the cliff, the plume would experience very little dispersion throughout the night. The lake breeze circulation in this case may further enhance higher than normal concentrations in the vicinity of the generating station.

It is concluded that the present study successfully provides a preliminary analysis of the dispersion climatology at the Bruce area based on observational data. Nocturnal inversions and lake breeze circulations may be important in causing the worst dispersion climatology to the area. Therefore, future studies should include observations of the vertical profiles of temperature and wind, both day and night.

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